

**MICROSTRUCTURAL ANALYSIS OF THE CAPE ROBERTS
CORE, WESTERN ROSS SEA, ANTARCTICA**

A Senior Thesis

Submitted as Partial Fulfillment of the Requirements
for the degree Bachelor of Science in Geological Sciences at
The Ohio State University

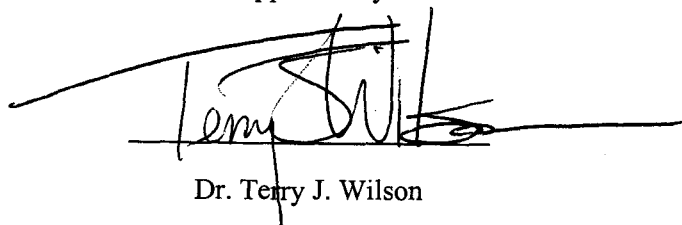
By

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2001

Approved by

A handwritten signature in black ink, appearing to read 'Terry J. Wilson', is written over a horizontal line. The signature is stylized with a large, sweeping initial 'T'.

Dr. Terry J. Wilson

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ABSTRACT

This work analyzes microstructures in core recovered offshore from Cape Roberts, in the westernmost Ross Sea of West Antarctica, in order to understand the rifting evolution of the Victoria Land Basin and its relationship to the uplift of the Transantarctic Mountain rift flank. The study focuses on textures, fabrics and grain-scale structures observed in thin sections of microfaults, veins, and clastic dikes. These observations are used to constrain the deformation mechanisms that produced these structures and the mechanical state of the sediment during deformation. These data, as well as macrostructural features observed in the core, are used to infer relative timing of faulting and sedimentation.

Clastic dikes are present throughout the core and commonly follow fault planes, indicating that injections of liquefied sediment used pre-existing faults as conduits for 'dewatering bursts'. Veins also commonly follow pre-existing fault planes and exhibit carbonate and pyrite growth and sparry calcite in open voids. In some veins fibrous calcite perpendicular to vein walls suggests opening-mode origin.

Microfaults are abundant and display two main types of textures. Some microfaults are characterized by grain-size reduction, poorly sorted angular grains and preferred orientation of clays and/or clast long axes parallel to fault zone walls; these are associated with brittle shear of dewatered and cohesive sediment. Others are 'shear zones' where bedding drag, sediment smearing, and no grain-size reduction indicate pre-lithification ductile flow of sediment by sliding of grains aided by abundant pore fluid. Diagenetic clays, zeolites and precipitation of calcite and sulfides along fault planes post-date microfaulting.

The close association of clastic injections, diagenetic mineralization, and faulting indicates that faulting was synchronous with deposition in the rift basin.

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To my father

TABLE OF CONTENTS

ABSTRACT.....	i
ACKNOWLEDGMENTS.....	ii
INTRODUCTION	1
CRP Drilling Project	1
Geologic Setting.....	1
Structures in CRP-3 Core.....	4
Conditions of CRP Deformation.....	8
<i>Depth of burial and likely temperature gradients</i>	<i>8</i>
<i>Mechanical state of the sediment</i>	<i>8</i>
Study Objectives	9
FRACTURE TYPES AND DEFORMATION MECHANISMS.....	12
Fracture Modes	12
Deformation Mechanisms	15
Mechanical State of the Sediment.....	16
Criteria to Recognize Fracture Types and their Deformation Mechanisms	18
<i>Clastic Dikes.....</i>	<i>18</i>
<i>Veins</i>	<i>19</i>
<i>Shear Zones in Incompletely Lithified Sediment</i>	<i>21</i>
1. <i>Shear Zones.....</i>	<i>21</i>
2. <i>Scaly Fabric.....</i>	<i>22</i>
<i>Cataclastic Fault Zones.....</i>	<i>23</i>
1. <i>Microfaults.....</i>	<i>23</i>
2. <i>Breccia, Cataclasite and Gouge</i>	<i>23</i>
Relative Timing.....	25
<i>Cross-cutting relations</i>	<i>25</i>

<i>Overprinting structures or textures</i>	25
<i>Mechanical state of the sediment</i>	25
<i>Diagenetic relations</i>	26
MICROSTRUCTURES OF CRP-3 CORE FRACTURES	27
Methodology	27
Descriptions	27
Clastic Dikes	28
<i>Clastic dikes with fault dips</i>	28
<i>Clastic dikes in dolerite breccia</i>	30
Veins	33
<i>Veins with fault dips and veins with en echelon geometry</i>	33
<i>Calcite veins with conjugate geometry</i>	38
<i>Cemented bands</i>	39
Microfaults	40
<i>Shear zones in partially lithified to unlithified sediment</i>	40
<i>Faults in cohesive to lithified sediment</i>	47
<i>Faults in the Beacon Sandstone</i>	51
DISCUSSION AND CONCLUSIONS	53
REFERENCES	57

INTRODUCTION

CRP Drilling Project

The Cape Roberts Project (CRP) is an international consortium of scientists from Australia, the United Kingdom, Germany, New Zealand, Italy, and the United States of America. The project undertook stratigraphic drilling in the western Ross Sea, Antarctica (Figure 1). The purpose of this project is twofold: (1) to study Antarctic glacial changes and their relation to and effect on global sea level changes, and (2) to study the rifting of Antarctica and formation of the Victoria Land Basin and the Transantarctic Mountains Front (Cape Roberts Science Team, 1998).

Three drilling seasons have taken place at Cape Roberts during the austral summers of 1997, 1998, and 1999. All together, over 1500 m of core have been successfully recovered (Cape Roberts Science Team, 2000). The cored interval spans from a thin upper section of Quaternary and Pliocene glacial marine sediment, through strata from Early Miocene (*c.* 17 Ma) to Early Oligocene or latest Eocene (?) age (*c.* 35 Ma), into mid-Devonian bedrock (Figure 2) (Cape Roberts Science Team, 2000). The last drill hole, Cape Roberts Project-3 (CRP-3), recovered *c.* 940 meters of core and is the focus of this study.

Geologic Setting

The cores from the Cape Roberts Project were recovered offshore of Cape Roberts, a small promontory in McMurdo Sound, western Ross Sea (Cape Roberts Science Team, 2000). The sites lie along the boundary between the Victoria Land Basin and the Transantarctic Mountains of East Antarctica (Figure 1) (Cape Roberts Science Team, 1998). The Victoria Land Basin is a large basin within the West Antarctic Rift System, which is adjacent and parallel to the Transantarctic Mountains, so that their deformational histories are likely to be linked (Cape Roberts Science Team, 1998).

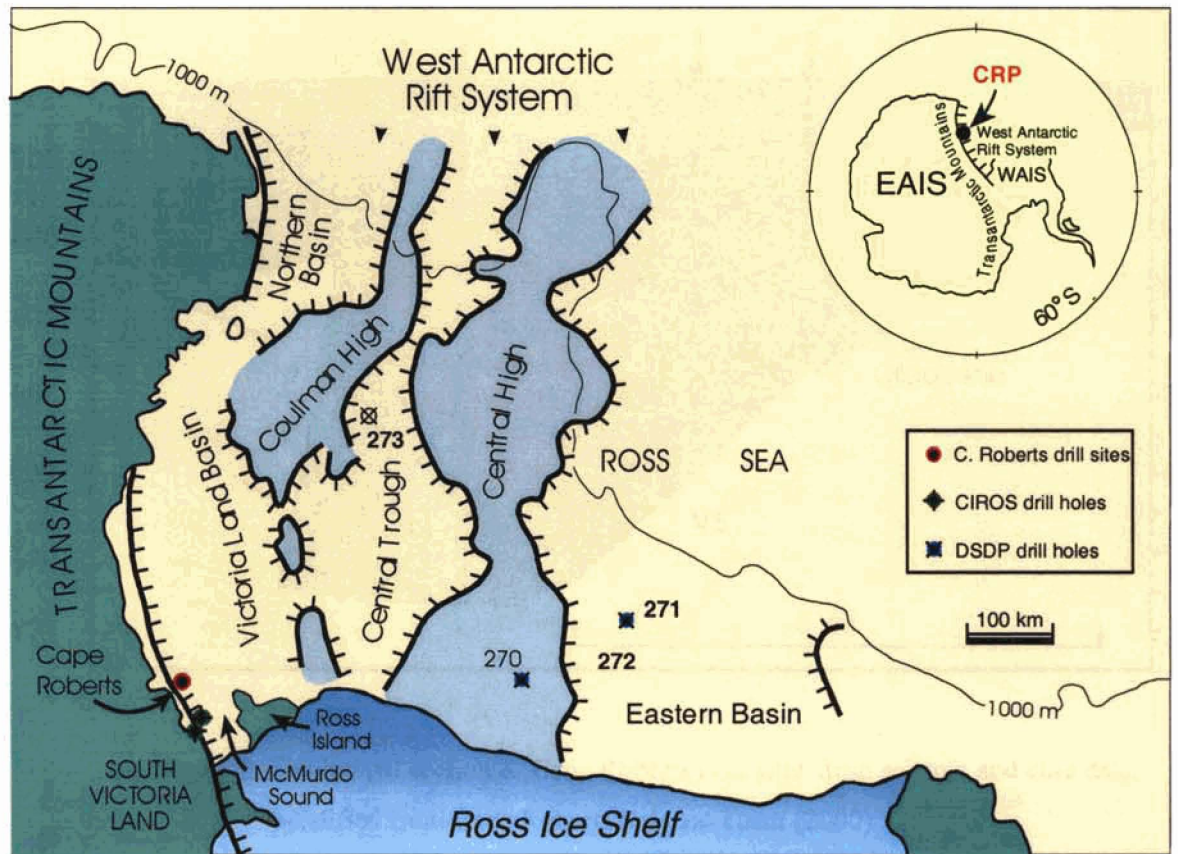


Figure 1. Tectonic outline map of the Ross Continental Sea Shelf. From Cape Roberts Science Team (2000).

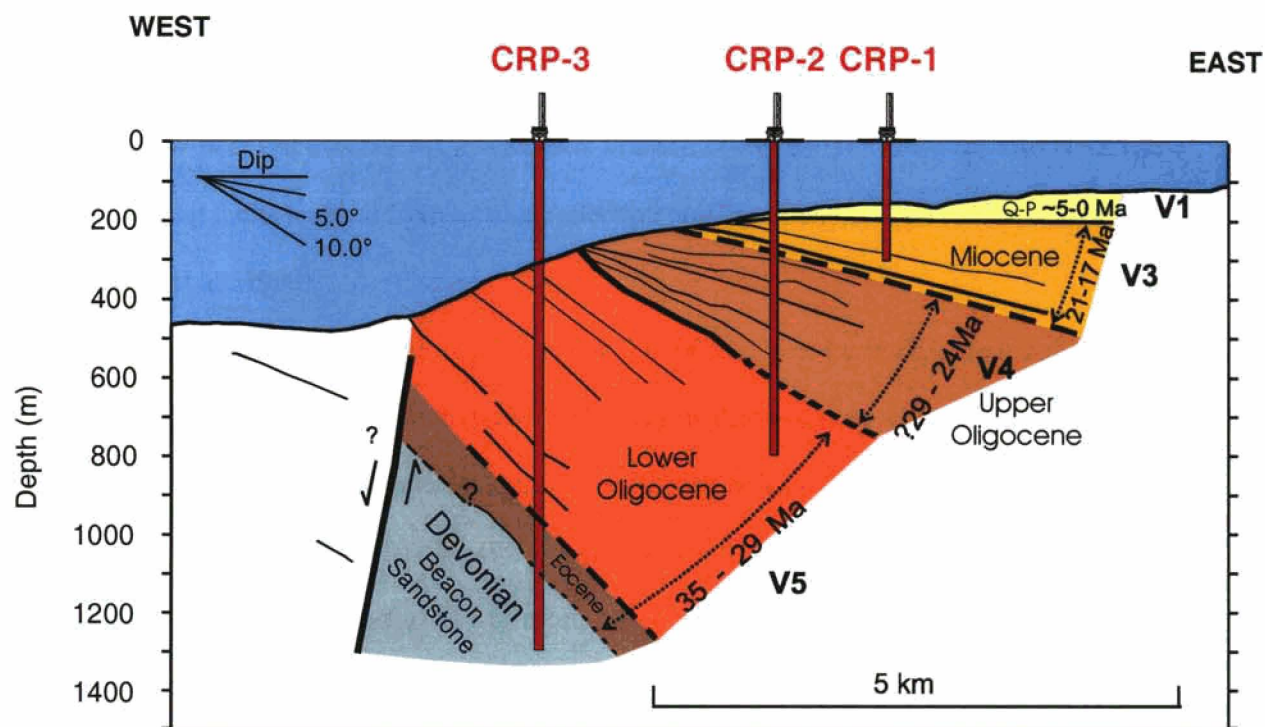


Figure 2. Geological section of Cape Roberts drill sites from seismic and core data.
Modified from Cape Roberts Science Team (2000).

Near Cape Roberts, the Victoria Land Basin strata dip 10 to 15° seaward (Figure 2), allowing progressively older sedimentary rocks to be sampled in CRP-1, CRP-2 and CRP-3 (Cape Roberts Science Team, 2000). The fault system that forms the boundary between the Transantarctic Mountains and the Victoria Land Basin is known as the Transantarctic Mountain Front, and trends NNW near Cape Roberts (Cape Roberts Science Team, 2000). There are also NNE and ENE trending faults mapped from seismic reflection profiles offshore Cape Roberts (Figure 3) (Hamilton et al., 1998).

In the CRP-3 drillhole (Figure 4), the first 400 m of core is of Early Oligocene age and consists of fine-grained muddy sandstones and sandy mudstones, both with dispersed dolerite clasts, and subordinate conglomerate units (Cape Roberts Science Team, 2000). Diamictites are common in the upper 100 m, but become scarce lower in the section (Cape Roberts Science Team, 2000). From 400 mbsf to 823.11 mbsf, the core is of Early Oligocene to late Eocene (?) age and consists of sandstone (to c. 580 mbsf) and muddy sandstone (to c. 799 mbsf), both with subordinate conglomerates (Cape Roberts Science Team, 2000). Minor sandstone and massive clast-supported dolerite conglomerate comprise the lowest Cenozoic strata to c. 823.11 mbsf (Cape Roberts Science Team, 2000).

The rest of the core is mainly Devonian age quartzitic sandstone from the Beacon Supergroup (Cape Roberts Science Team, 2000). An interval of intrusive rock of probable Jurassic age, strongly altered and brecciated, is present between 901 and 918 mbsf (Cape Roberts Science Team, 2000). The reddish-brown quartzitic sandstone of the Beacon Supergroup is present down to the base of the core at 939.42 mbsf (Cape Roberts Science Team, 2000).

Structures in CRP-3 Core

Natural fractures in CRP-3 core are abundant and show a variety of fabrics and textures throughout the c. 940 m of core recovered (Cape Roberts Science Team, 2000).

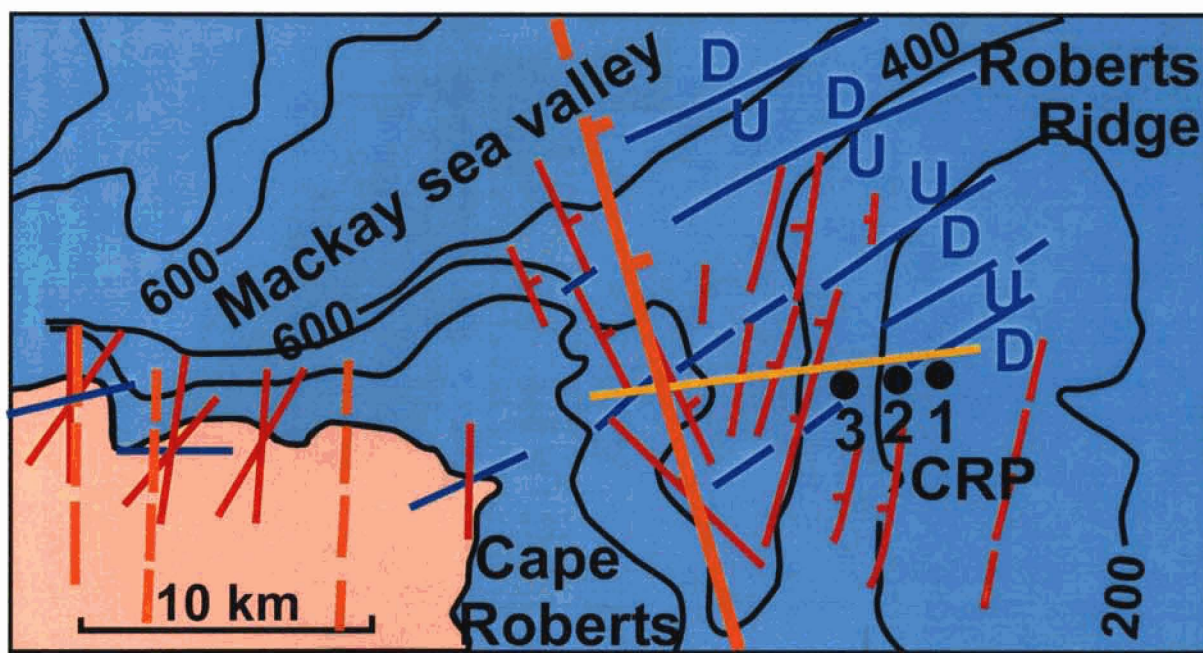
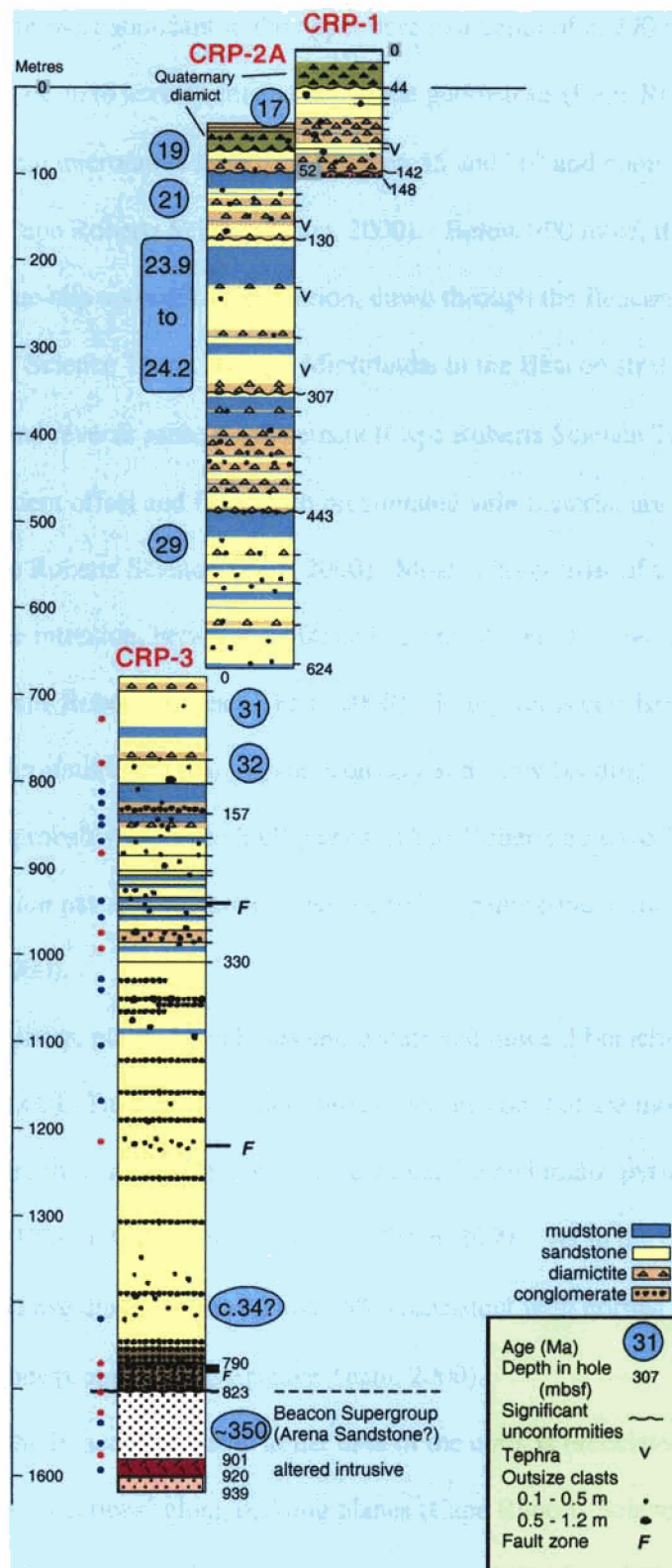


Figure 3. Structural setting of the Cape Roberts Project drill sites. Offshore faults mapped from seismic reflection profiles include the Transantarctic Mountains Front (orange, NNW), NNE and NNW normal faults (ticked orange), and ENE high angle faults (blue). From Hamilton et al. (1998). Normal fault trends on shore from Wilson (1995). Cross section modified from Hamilton et al. (1998)..



Normal microfaults are most abundant in the upper core to a depth of c. 790 mbsf. These faults have typical offsets of up to several cm and conjugate geometries (Cape Roberts Science Team, 2000). Most of these microfaults have dips between 55 and 70° and commonly have well-developed slickensides (Cape Roberts Science Team, 2000). Below 790 mbsf, the microfaults change to primarily oblique-slip and strike-slip motion, down through the Beacon and to the end of the core (Cape Roberts Science Team, 2000). Microfaults in the Beacon strata have moderate dip angles—45 to 55°—and reverse sense displacement (Cape Roberts Science Team, 2000).

Fractures with no evident offset and filled with precipitated vein material are also common throughout the core (Cape Roberts Science Team, 2000). Most veins consist of calcite, and pyrite fill is common. Within the intrusion, between c. 900 and 920 mbsf, vein fill consists of a light green-fibrous material (Cape Roberts Science Team, 2000). Many veins consistently show the same dip angles as the microfaults, have conjugate geometry and show bedding offset, all of which suggests the veins probably followed fault planes (Cape Roberts Science Team, 2000). Some veins show *en echelon* patterns and are considered to be opening-mode fractures (Cape Roberts Science Team, 2000).

Clastic dikes display sharp, planar boundaries and occasional upward branching (Cape Roberts Science Team, 2000). They are abundant throughout the core but are more common in the Oligocene strata, where they are typically cemented by calcite and minor pyrite and have widths ranging from 3 to 10 mm (Cape Roberts Science Team, 2000). As in the case with many of the veins, clastic dikes have dips between 40 and 75°—consistent with normal fault dips—and may also follow fault planes (Cape Roberts Science Team, 2000).

More than a third of the Beacon sediment, at the base of the core, is brecciated into steep breccia zones and breccia 'injections' along bedding planes (Cape Roberts Science Team, 2000). Breccia fragments are typically subrounded to angular and many clasts show bedding rotation suggesting lithification occurred prior to the brecciation (Cape Roberts Science Team, 2000).

Conditions of CRP Deformation

Depth of burial and likely temperature gradients

Based on the composite stratigraphic column determined for the CRP-1 and CRP-2 drillholes, an estimated 750 m of sedimentary rock was originally above the stratigraphic section cored in the CRP-3 hole (Cape Roberts Science Team, 2000). Therefore the depth of burial of the Oligocene sediments in CRP-3 ranged from 750 to 1575 meters. Assuming an average lithostatic gradient of $\sim 25 \text{ MPa/km}$, this corresponds to a range of *c.* 20–40 MPa lithostatic pressure. A downhole temperature log was completed in the CRP-3 drillhole, which yielded an average present-day geothermal gradient of 28.5°C/km (Cape Roberts Science Team, 2000). Values in other drillholes in the region have yielded higher estimates of up to 35°C/km . If similar gradients held during CRP-3 deformation, temperatures would have been somewhere in the range between *c.* $25\text{--}55^\circ\text{C}$. It is possible that temperature gradients were higher when rifting was active in the Oligocene. However, it is clear the deformation of CRP-3 sediment took place at low temperatures and confining pressures, within *c.* 1.5 km from the surface of the earth.

Mechanical state of the sediment

Studies on CRP-3 core have provided the means for a better understanding of the relative timing of Victoria Land Basin formation. Biostratigraphic work shows that rifting started in the Late Eocene or Early Oligocene, and that the thick sediment fill in the basin is almost completely of Oligocene age (Cape Roberts Science Team, 2000). Abundant microfaults and less common large-scale faults in the core cut across the youngest Oligocene age sediment and must, therefore, be Oligocene or younger in age, which in turn implies that faulting and deposition in the basin were synchronous (Cape Roberts Science Team, 2000). Since some faults may have formed shortly after deposition of the Oligocene strata and others formed afterward and possibly up to the

present, deformation of unlithified as well as lithified material needs to be taken into consideration.

From all of this information it is now possible to predict the likely deformation mechanisms and fault rock types (Figure 5) developed in response to those mechanisms at the CRP-3 site (Figure 6) show that at the low temperature and confining pressure conditions of CRP-3, it is expected to find deformation mechanisms ranging from pressure solution and mechanical twinning, at low temperatures and moderate differential stress, to fracture, frictional sliding, and cataclastic flow as differential stress increases. Dislocation glide and dislocation creep are within the domain of high differential stress and temperature, which are not likely conditions at CRP-3. In the shallow setting of CRP-3 at approximately 1500 m of depth or less, the textures and structures exhibited by fault rocks are expected to be those of the incohesive cataclasite series, more specifically breccias and gouge (Figure 5).

Study Objectives

In this study, textures, fabrics and grain scale microstructures in natural fractures in CRP-3 core are documented from thin section analysis. Natural fracture types studied include microfaults, veins, clastic dikes and breccias. The microscopic textures and compositions of these features are used to evaluate the structure types assigned during macroscopic core logging, to assess questions such as whether veins always formed along faults or as later, opening-mode fractures. The microstructural data are used to evaluate the deformation mechanisms that produced the core structures and the mechanical state of the sediment during the deformation. Together with the macrostructural features observed in core samples, these observations are used to infer relative timing of faulting and sedimentation in the Victoria Land Basin.

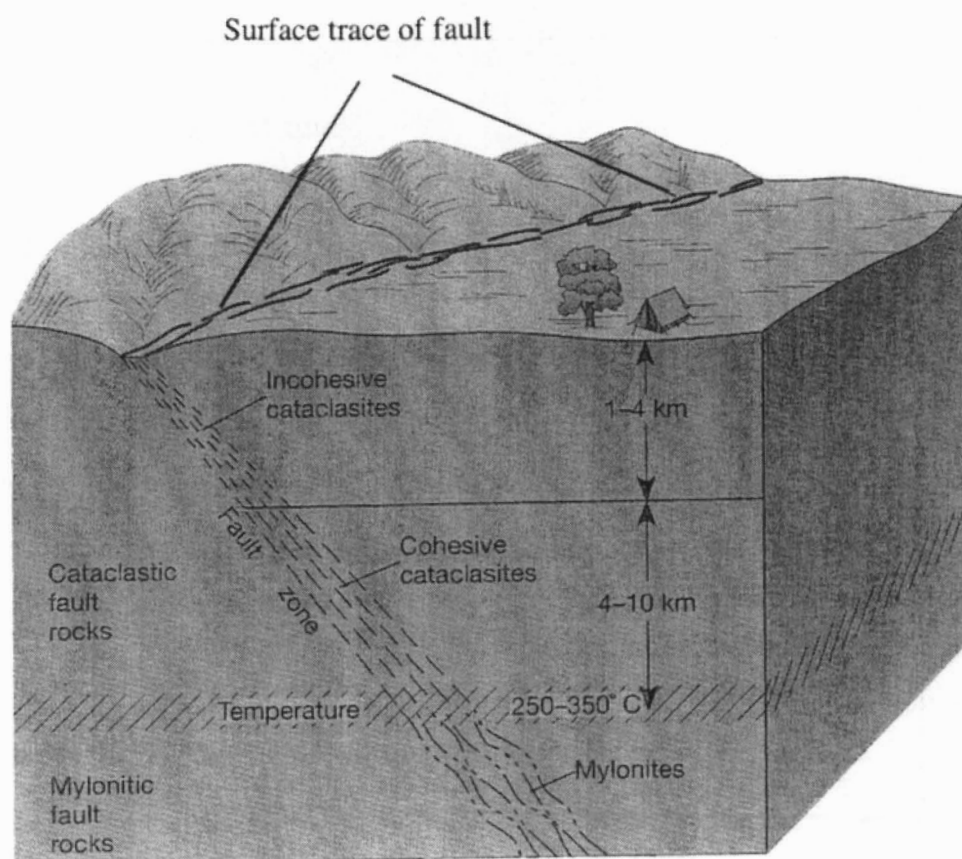


Figure 5. Variation with depth of the type of fault rock within a fault zone.
From Twiss and Moores (1992).

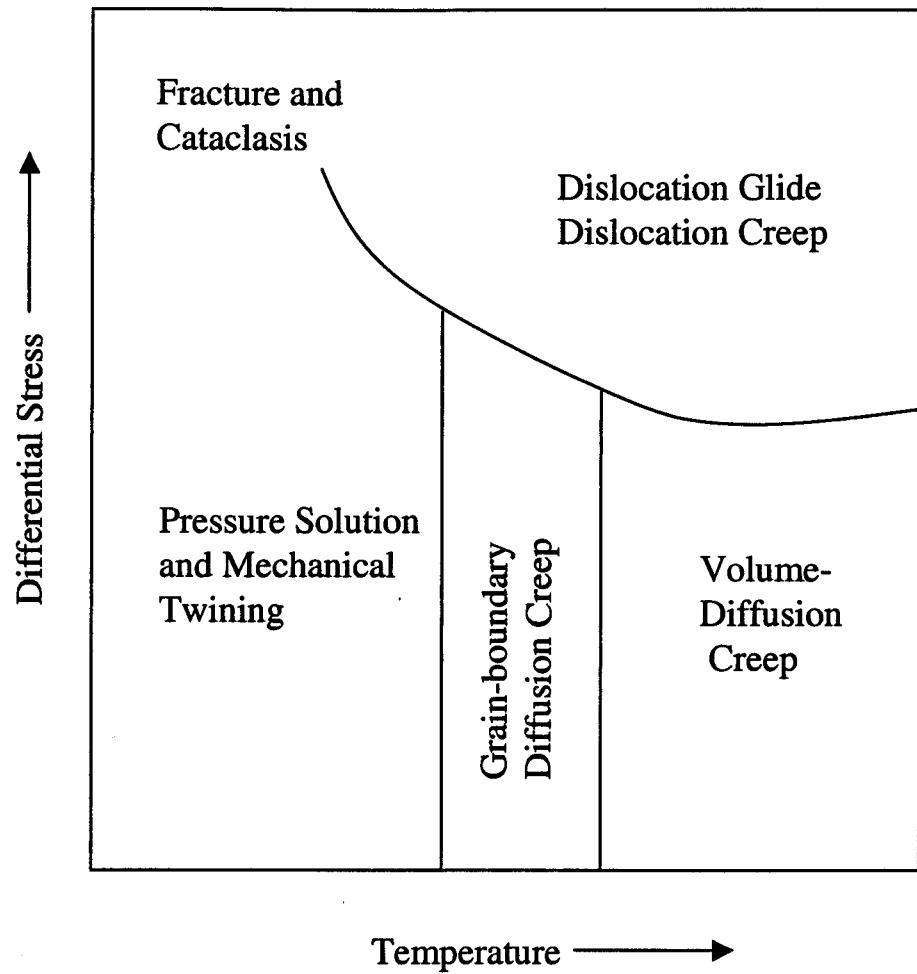


Figure 6. Simplified deformation map showing the general conditions where each deformation mechanism dominates relative to one another
From Davis (1984).

FRACTURE TYPES AND DEFORMATION MECHANISMS

Fracture Modes

The term fracture refers to a physical break or discontinuity in a rock due to stresses higher than the rock's strength (van der Pluijm & Marshak, 1997). Shear fractures are those fractures with a small but observable displacement parallel to the fracture plane (van der Pluijm & Marshak, 1997). Shear fractures (Mode II and Mode III; Figure 7) originate when stress is applied to the rock and small, preexisting microcracks grow together along a narrow zone—typically oriented at a 30° angle to the maximum compressive stress (Figure 8)—and converge into a surface on which sliding may then take place (van der Pluijm & Marshak, 1997). If stress is still ongoing, the fracture will grow into its own plane and develop into a fault with a more significant displacement. The sliding and grinding of grains past one another result in the development of a cataclastic fault zone (van der Pluijm & Marshak, 1997).

Opening mode fractures (Mode I; Figure 7) have no measurable displacement parallel to the fracture surface, instead, the cracks open perpendicular to their walls, and typically originate at sites of preexisting cracks (van der Pluijm & Marshak, 1997). When stress is applied to a rock with a preexisting microcrack, concentration of stress builds at the crack tip; once the stress at this point overcomes the rock's strength, the crack grows and propagates throughout the rock (van der Pluijm & Marshak, 1997). Stress at the crack tips is sometimes caused by fluid entering a microcrack and increasing pore pressure (van der Pluijm & Marshak, 1997). Fractures originating in this manner will propagate as long as fluid pressure within the crack exceeds the rock strength plus the minimum compressive stress acting perpendicular to the crack walls (van der Pluijm & Marshak, 1997). Veins and fluid-rich sediment injections commonly form in this way.

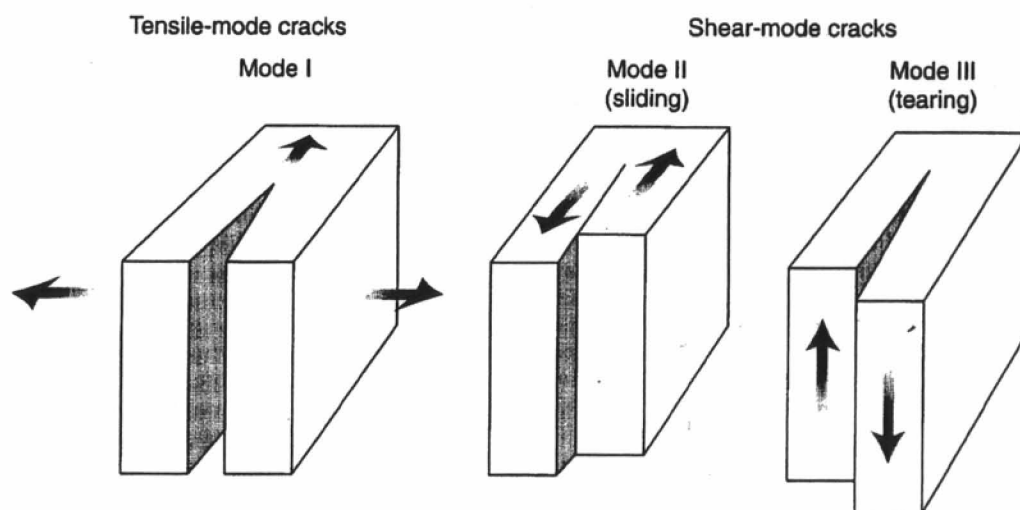


Figure 7. Three different modes of crack-surface displacement.
Van der Pluijm & Marshak (1997).

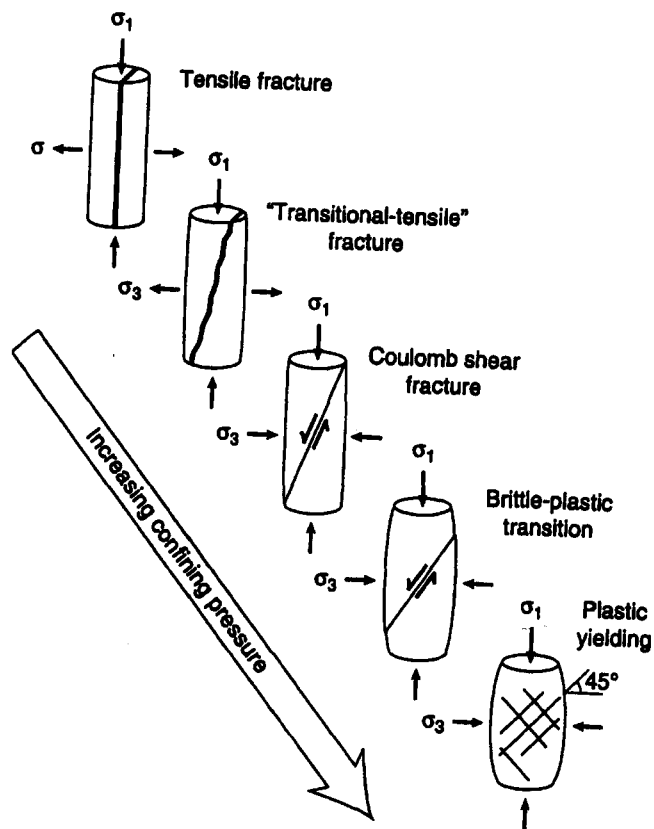


Figure 8. Geometries of different fracture modes with respect to principal stresses and increasing confining pressure. Van der Pluijm & Marshak (1997).

Deformation Mechanisms

Both the composition of a rock and the environmental conditions in which it deforms when it is subjected to stress control how it deforms at the grain-scale and the microstructures resulting from that deformation (Knipe, 1986). Some of the major mechanisms by which rock deforms are pressure solution, crystal plasticity, cataclastic flow and frictional sliding (Figure 6) (Knipe, 1986). Note that all these mechanisms are not exclusive of each other and can all operate at the same time in a rock, but it is common that one mechanism predominates over the others.

Fracture, frictional sliding and cataclasis occur at low to moderate confining pressure, low temperature and high stress (Figure 8) typical of the upper crust (Knipe, 1986). Fracturing and crushing at the grain-scale produce gouge and breccias (Knipe, 1986). When the fluid pressure environment is high, a lower stress is needed for the grains to fracture and slide past each other (Knipe, 1986).

Pressure solution accommodates deformation by transferring material from sites of high normal stress to areas of low normal stress in the presence of fluids and along grain boundaries (Knipe, 1986). Pressure solution typically occurs at low temperature, low stress and low to high confining pressure, and it produces well-developed microstructures such as sutured grain boundaries, pressure shadows, overgrowths and stylolites (Knipe, 1986).

Dislocation glide and creep occur at moderate to relatively high temperature and stress (Knipe, 1986). In these conditions, recrystallization and undulose and blocky extinction within crystals are some of the most typical microstructures (Knipe, 1986). Crystal-plastic mechanisms allow lattice distortion—and therefore grain-shape change—within grain boundaries by either twinning or dislocation glide and creep (Knipe, 1986).

Sediments undergoing lithification as well as weakly lithified sediments may deform by “independent particulate flow,” a mechanism active at high fluid pressures and low confining pressures and characterized by the sliding of grains past one another along grain boundaries, (Knipe, 1986) and rotation of grains. According to Maltman (1987), sedimentary rocks with

evidence of little intragrain deformation but significant shearing most likely underwent pre-lithification deformation.

In general, frictional sliding, cataclasis and pressure solution processes are the primary deformation mechanisms in the upper crust, changing to cataclastic flow with increasing depth. Ductile behavior in the middle and lower crust is generally accommodated by crystal plasticity.

Mechanical State of the Sediment

In the context of deformation, the term 'soft sediment' applies to a sediment's resistance to shearing stress and therefore its cohesiveness (Maltman, 1984). However, the mechanical properties of soft sediment are intimately related to its textural, petrographic and mineralogical attributes, and the changes in these at each diagenetic stage (Maltman, 1984). As a guideline, soft sediment is ductile material in which grain-boundary sliding is the primary deformation mechanism and where typically minimal or no intra-granular deformation is observed (Maltman, 1984).

Confining pressures, pore pressures, and temperature during burial are important factors to take into consideration when dealing with the lithification state of a sediment (Maltman, 1984). As sediments undergo water loss—and therefore, porosity loss—and diagenetic changes, their ductility decreases and their cohesive state increases, causing intragranular deformation such as that indicated by the presence of twins, lamellae, pressure solution structures, and/or grain fractures (Maltman, 1984).

Note, however, that as sediments evolve from unlithified to partially lithified to lithified, a particular deformation mechanism is not the only one operating. In partially lithified sediments, for instance, grain-boundary sliding may be the predominant process of deformation, but there may be increasing evidence of grain breakage or intragranular deformation processes as well (Maltman, 1984) (Table A).

Table A

Pre-lithification vs. Hard-Rock Structures	
Lithified Rock	Unlithified/Partially Lithified
<ul style="list-style-type: none"> • Intragranular plastic deformation: twins, deformation bands & lamellae • Pressure solution • Cataclasis dominant <p>Angular grains, floating in matrix</p> <p>Poorly sorted, wide range of grain size</p> <p>Intragranular and transgranular fractures</p> <ul style="list-style-type: none"> • Associated with cogenic mineralized fractures <p>Crack-seal veins</p> <p>Fibers perpendicular to walls</p> <ul style="list-style-type: none"> • Fractures that cut across clasts and matrix 	<ul style="list-style-type: none"> • Shear zones: offset, with no discontinuity or grain breakage • Association with sediment injections • Cross-cut by feature of known stage of lithification (e.g., concretion) • Structure restricted to layer bounded by depositional upper contact; or truncated by bounding surfaces that are demonstrably not hard-rock structures (e.g., but by burrow or sediment injection) • One of family of cogenic structures, some of which are clearly pre-lithification (e.g., clastic dykes filling faults) • Appropriate overall sedimentary and deformational setting

Table A. Summary of criteria to recognize pre-lithification and hard rock structures

Criteria to Recognize Fracture Types and their Deformation Mechanisms

Clastic Dikes

Clastic dikes are forcefully injected sedimentary structures associated with fluid-sediment movement as a response to loading and/or tectonic stresses (Collinson, 1994). Dikes form from various lithologies and are intruded within a large range of 'hosts', however, in order for a dike to be injected the host material must be somewhat strong, that is, it must be lithified or clay must be present to give the host rock some cohesion (Collinson, 1994). Evidence for fracturing of cohesive material is found when angular to subangular fragments of host rock are incorporated within the dike (Lundberg & Moore, 1986). The presence of clasts, such as 'lonestones' in diamictites, indented into the dike margins, indicates compaction after dike emplacement.

Dikes typically have sharp, planar boundaries, cross cut bedding, and may reach widths up to tens of centimeters (Collinson, 1986). Offset of bedding across a dike is present where a pre-existing fault plane is filled by injected clastic material (Collinson, 1986). Clastic injections may intrude downward from overlying source beds, however, Dunne and Hancock (1994) as well as Maltman (1986) agree that dikes are most commonly intruded upward from below or, in some cases, from the side. Observation of the dike termination geometries can resolve the injection direction (Pickering, 1983).

The material within a dike may vary from sandstone to siltstone to mudstone, and its sedimentary intrusive origin needs to be assessed. If fragments derived from the host rock are present within the dike, then forceful injection of the material is demonstrated (Collinson, 1986), however this texture may resemble cataclastic material in a fault. However, if the dike fill is different in composition and grain size from the host rock, and the dike followed instead of truncated the host rock grains, it is clearly of sedimentary origin (Collinson, 1986). Although sandstone clastic dikes typically lack internal fabric, there may be a weak foliation parallel to the dike walls, suggesting some amount of flow-related shearing during emplacement (Collinson,

1986). It is difficult to prove if clastic dikes formed as dewatering channels due to faulting, as a result of overpressure from the overlying sediments, or if they 'flowed' into a pre-existing fracture or fault plane (Collinson, 1986). Davison (1986) suggests that early faulting and upward injected clastic dikes are closely related and the latter often follow fault planes. Others suggest that the regular, planar edges of a dike and the typical lack of displacement parallel to dikes implies opening-mode fracturing during emplacement of a slurry intrusion (Lundberg & Moore, 1986; Dunne & Hancock, 1994). Note, however, that clastic dikes may be injected into pre-existing fault planes and that cataclastic material may, as well, be emplaced within a fault plane.

Veins

Veins are nearly planar fractures filled with materials precipitated from fluids, mainly calcite, dolomite, quartz and pyrite. Some veins (Figure 9) form by chemical replacement of the host rock and characteristically display non-matching walls—due to solubility differences in host rock composition—and mineral replacement in favorable layers (Hobb et al., 1976; Dunne & Hancock, 1994). Pre-existing fabric in the host rock stays preserved across the vein fill and there is no evidence of offset (Hobb et al., 1976).

Other veins form by fluid precipitation into fractures that were already there, or that were opening at the same time as the vein material precipitated (Dunne & Hancock, 1994). These veins show offset of early structures but no shear component across the fracture, and the vein's walls are of equal composition (Hobb et al., 1976). Commonly, the vein texture consists of either equant or fibrous crystals. Crystal fibers are characteristic of a fracture that is opening while filling takes place (Hobb et al., 1976). Fibrous veins are long, thin crystals that grow parallel to the stretching direction of the vein, and are often used as shear sense indicators (Figure 10) (Dunne & Hancock, 1994). Fibers grown by crack-seal processes record the amount of vein growth, while inclusion trails—fragments of wall rock embedded in the fibers—record true displacement direction (Dunne & Hancock, 1994). Blocky crystals (also known as sparry

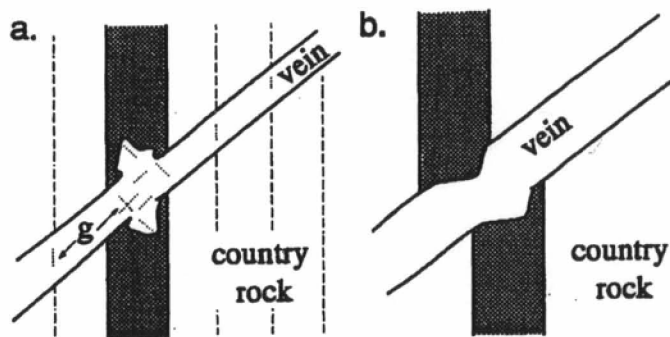


Figure 9. (a) Replacement veins with non-matching walls. (b) Dilation Vein.
From Dunne & Hancock (1994).

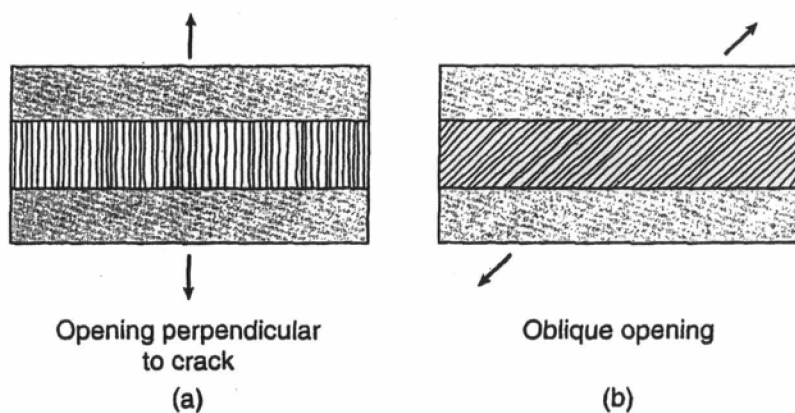


Figure 10. Shear sense indicators from fibrous calcite crystals. From van der Puijm & Marshak (1997).

crystals) with equant geometry and some crystal faces indicate precipitation into open space. This type of crystal may form in cavities that stay open sufficiently long for the crystals to form or in other cases by recrystallization of fibrous veins.

Veins that have filled fracture arrays formed by the accommodation of shear displacement across a zone are termed *en echelon* veins (Dunne & Hancock, 1994). These are typically arrays of veins displaying sigmoidal shapes and because of their relationship with shear displacement are often good shear sense indicators (Dunne & Hancock, 1994).

Mud-filled veins—also called ‘vein structures’—are thin, planar or curvilinear, and are filled with sediment that is commonly of the same composition as that of the host rock but finer grained (Lundberg & Moore, 1986). Such ‘vein structures’ may appear as uniformly spaced, subparallel bundles parallel to bedding or as individual veins almost perpendicular to beds (Taira, Byrne & Ashi, 1992). According to Maltman (1994) sediment-filled veins commonly appear in conjugate sets with a filling that is darker but of the same composition as that of the host rock (the darker appearance is due to the presence of disseminated pyrite), and lacking common ‘vein’ minerals such as quartz and calcite. Lundberg and Moore describe vein structures from deep sea cores as lighter in color than the host from which they are derived but sometimes stained or coated (1986). Mud-filled ‘vein structures’ are interpreted to form by sediment injection (Hancock, 1994) and therefore are related to clastic dikes.

Shear Zones in Incompletely Lithified Sediment

1. Shear Zones

Ductile shear zones are intensely deformed areas without physical discontinuity or break in the rock, and where shear deformation and distortion of marker beds is restricted to a planar zone (van der Pluijm & Marshak, 1997). Typically, ductile shear zones are restricted to conditions of high temperature and/or confining pressure (Figure 5), although grain size or strain rate may be important factors (van der Pluijm & Marshak, 1997).

On the other hand, shear zones are also common in sediment with high water content deformed prior to lithification. Deformation is localized within a narrow band or zone rather than throughout the width of the material (Arch, Maltman & Knipe, 1988). They are characterized by both minimal grain deformation and intragranular breakage, a decreased porosity when compared to the host rock, and dragging and/or smearing of sediment along the shear zone (Antonelli, Aydin, & Pollard 1994). Microscopically, soft-sediment shear zones are more or less planar, but in sediment with higher water content the zones typically become more narrow and anastomosing (Arch, Maltman & Knipe, 1988). The internal fabric is characterized by the orientation of the clays, typically parallel or nearly parallel to the zone margins (Maltman, 1987), that can be easily seen in thin section as brightly illuminated narrow bands.

2. Scaly Fabric

Scaly fabrics are features that occur in association with thrust faults, in unlithified material within fault zones in sedimentary sequences (Moore et al., 1986). Scaly fabrics are most commonly found in the mudstones of accretionary prisms, at low temperature and pressure and high pore-pressure (Moore et al., 1986). Studies in the Barbados Ridge area suggest scaly fabric develops preferentially in underconsolidated smectite-rich mudstone, since other mudstones found in the area—specifically calcareous mudstone—only show weak scaly fabric or none at all (Moore et al., 1986). According to Moore et al. (1986) this suggests a strong relationship between lithology and the fabric development.

Macroscopically, scaly fabric is characterized by smooth, polished, slickenlined surfaces and anastomosing fabric that may flake easily (Moore et al., 1986). Microscopically, it consists of thin, anastomosing zones of clays with either a strong orientation parallel to the slip surface, or at a low angle to the slip surface (Moore et al., 1986). At low magnification, these shear zones are easily discernible by an optically patchy extinction due to the orientation of the clays within the zone (Maltman, 1987).

Cataclastic Fault Zones

1. Microfaults

Microfaults are characterized by the small offset—from millimeters to less than 5 centimeters—they accommodate (Cashman & Cashman, 2000) and are the product of brittle deformation where mechanical fracturing of a rock's grains create microfault fabrics.

Typical characteristics of microfaults are truncation and offset of bedding, grain-size reduction with a wide range of grain shapes and orientation of clays parallel to zone walls (Antonelli, Aydin, & Pollard 1994). Cracking is common, especially where grains are 'touching' other grains of similar size. Sorting, usually poor at the early stages—when large and still intact grains tend to get surrounded by smaller size grains—improves as cataclasis progresses (Antonelli, Aydin, & Pollard 1994). These cracked grains are most abundant closer to the microfault walls and die out as the distance increases from the wall inward (Labaume, 1987).

A lack or few calcite grains within the fault zone, when its presence in the surrounding rock is considerable, may further confirm a cataclastic origin since calcite would have been the first mineral to 'disappear' by cataclasis (Labaume, 1987). In most cases clay development and a mixture of finely crushed grain fragments and calcite creates a dark 'matrix' that surrounds the smaller grains (Labaume, 1987).

2. Breccia, Cataclasite and Gouge

Breccias (Figure 5) commonly form as fault rocks due to brittle deformation at shallow depths. Fault rock breccias are characterized by more than 30% volume of angular clasts (Passchier and Trouw, 1996). Fragments may be derived from the host rock and/or from fragments of pre-existing veins, all set within a fine-grained matrix (Passchier & Trouw, 1996). Breccias showing precipitation and crystal growth of minerals from fluids in voids are termed cohesive breccias and are characterized by a larger size range of fragments and a less clear

distinction between host rock walls and the breccia itself (Passchier & Trouw, 1996). Because of the precipitation mechanisms responsible for the formation of cohesive breccia, fragments are often cross cut by cracks filled with vein-forming minerals such as calcite, quartz and chlorite (Passchier & Trouw, 1996). Breccia clasts commonly show rotation with respect to one another and to the host rock due to shear during faulting (Passchier & Trouw, 1996). Breccia dikes are breccia material that has been squeezed into openings formed during faulting and often branch into the host's rock bedding (Davis, 1984). These dikes are the result of high pore fluid pressure and strain rate, which probably caused the loss of cohesion in the host rock and allowed the brecciation to occur (Labaume, 1987).

In addition to fault-related deformation, breccias can also form by other processes. Sedimentary breccias are characterized by the roundness of their fragments floating in a lithified mud matrix whereas tectonic/cataclastic breccias show fragmentation features and *in situ* brecciation, where clasts may be angular to subrounded and of the same composition as the host rock (Lundberg & Moore, 1986). Phreatomagmatic breccias are caused by subsurface magmatic movement and/or magmatic-related hydrothermal activity where overpressured subsurface fluids lead to brecciation (Sillitoe, 1985).

Cataclasites (Figure 5) are angular clasts and/or fragments in a large range of sizes and random fabric, set within a fine-grained matrix (van der Pluijm & Marshak, 1997). Features commonly seen at the grain scale are cracks, sharp, straight boundaries, transgranular fractures and, in some cases, slickensides and slickenfibres may be present (van der Pluijm & Marshak, 1997). Cataclasites consist of less than 30% visible fragments and typically form in fault zones in the upper crust; further mechanical crushing of a cataclasite develops into a very fine-grained rock called gouge (van der Pluijm & Marshak, 1997). Precipitation of vein material such as quartz, calcite and chlorite tends to cement cataclasite fragments into cohesive rock, thought to develop at greater crustal depths (van der Pluijm & Marshak, 1997).

Relative Timing

Cross-cutting relations

Relative timing of events can be inferred by observation of crosscutting relationships among microstructures. Clastic dikes, veins, and faults are younger than the sediments and/or features they crosscut.

Overprinting structures or textures

There are instances in which clastic dikes are known to have been injected upwards into fault planes (Davison, 1987). It is also well documented that vein material often precipitates—or replaces material—along fault planes. If it can be shown that pre-existing fault textures are cut by sub-parallel dikes or veins, or that vein material replaces the textures, then they must be younger than the fault they fill.

Mechanical state of the sediment

Structures developed in lithified rock must be younger than structures formed in unlithified material. Although textures and microstructures may not always be diagnostic of the mechanical state at the time of deformation, some indicators may be used. For example, clastic dikes must form when at least some strata are not fully lithified, for the injection of semi-liquefied or slurry material in the dikes to occur.

Calcite veins can be of use to record the mechanical state of the host sediment. Veins that appear 'dirty', have irregular walls and anastomose around grains rather than cutting through them, are interpreted to indicate early diagenesis and sediment lithification (Byrne, 1994). The 'dirt', when observed at high magnification, is simply tiny clay particles that became part of the vein fluids during vein precipitation (Byrne, 1994). Hence, 'dirty calcite' in a vein or fault fill implies the structures formed during lithification. Partial lithification of sediment can be inferred

by veins that appear 'clean', have suture-like walls, and commonly contain host rock grains and/or matrix fragments (Byrne, 1994). The sediment matrix is still weak enough to let the calcite open and precipitate, but hard enough for the small particles to stay cohesive and not mix in with the vein fluids (Byrne, 1994). Where 'clean' fibrous calcite veins appear clear and free of microscopic particles, have sharp, straight walls and cut through the framework grains of the sediment, then the veins likely formed when the host sediment was cohesive or even lithified (Byrne, 1994).

Diagenetic relations

If there is a documented sequence of different materials precipitated as cements or vein fills during diagenesis, then the presence of a particular mineral fill within a structure may yield relative timing information. In CRP-3 sediments, 'early' diagenetic minerals include Low-Mg calcite, authigenic siderite, and authigenic zeolites, whereas 'late' minerals are smectites and sparry, no-Mg calcite (CRP Science Team, 2000; Aghib, in press).

MICROSTRUCTURES OF CRP-3 CORE FRACTURES

Methodology

Samples from the core (Figure 4) were selected according to their potential to show fabric and/or texture features, based on macroscopic core logging. From these samples, forty-nine covered and impregnated thin sections were prepared for microscopic analysis, the majority of them 2 x 3 inches in size for better texture analysis. Twenty-nine of them were investigated at low magnification under a stereomicroscope to record textural features. In fine-grained material, minerals and textures were observed under a petrographic microscope at higher magnifications.

Systematic descriptions of microstructures, fabrics, vein fillings and other features of interest were recorded and are presented in Tables B through D. Half-slab and whole core scans, as well as core photographs, were used to aid in the interpretation of microstructural relationships and/or textures and fabrics that were more evident at the macroscopic scale than in thin section.

In order to be able to relate the core fractures to larger-scale structures in the region, it is necessary to orient the core. At the time of core recovery, an arbitrary 'north' was prescribed by a line drawn along the core's length. In order to get true orientation of the core, features in images of from a borehole televiewer—an oriented scan of the inside of the drillhole—were matched with scanned images of the whole core (Paulsen et al., 2000; Jarrard et al., in press). Some of the samples used in this study have already been oriented and true geographic coordinates have been assigned.

Descriptions

In order to summarize and interpret the microstructures observed in the thin sections, the samples have been grouped together according to common macroscopic characteristics that may be significant for interpreting deformation mechanisms, kinematics or timing relationships. The macroscopic features were logged on the whole core. Following the discussion of each major

group of features, there are tables containing information about the most significant textural characteristics of each thin section. Other relevant information is also included, such as lithologies of both the host rock and the observed feature, macroscopic observations from the whole core, kinematic indicators if any, and orientation of the feature—for features from core that has not yet been oriented, only dip is provided.

Note that each sample was placed in the table according to their macroscopic characteristics, and the initial assignment to structural groups made during core logging. In cases where the microscopic analysis of each thin section reveals new features and/or textures, a new structural classification or interpretation is noted in the tables.

Clastic Dikes

Clastic dikes with fault dips

Clastic dikes commonly form as opening-mode fractures, which more commonly are nearly vertical. In CRP-3 core, however, most clastic dikes had dips between c. 50-80° more typical of shear fractures (faults). Two thin sections, 106.00-106.04, and 194.50-194.54 (Table B) were examined, to determine if the dikes are opening-mode fractures or if they followed pre-existing fault planes.

Although the host rock lithologies consist of sandy mudstone the dike fills are somewhat different in their textures. Both dikes consist of fine to medium-grained quartz sandstone—the first one containing more subangular to angular grains and the second one subrounded to subangular—that is moderately to well-sorted. There are grain size changes both across the dike's width and along the dike's length but, generally, the fill is coarser-grained than the host rock. This shows the dike fill was injected, not derived from the host rock. Xenoliths—either from the host rock or from lithologies not present in the host rock in the thin section—are scattered throughout both dikes.

Table B

CLASTIC DIKES					
SECTION ID DEPTH	HOST ROCK LITHOLOGY	MACRO- STRUCTURES	DIKE LITHOLOGY	TEXTURES	ATTITUDE
106.00-106.04	Sandy mudstone	Pyrite Fizzes Clastic Dike	Fine grained sandstone Subrounded to angular Grain size changes Coarser than host rock	Sharp contacts but 'wavy' edges Patches of oriented grains parallel to walls Branches seem to thin out upward? Xenoliths within dike (not from host rock) No fault evidence	Will be oriented F#: 363 Dip: 55°
194.50-194.54	Sandy mudstone and muddy fine grained sandstone	Pyritized Clastic dike	Well sorted Moderate to well rounded Coarser than host rock	Crosses and cuts bedding Clay oriented parallel to walls inside zone Pyritized matrix and no calcite Xenoliths from host rock Irregular grain size changes across Upward injection apophysis	Will be oriented F#: 583 Dip: 75°
790.37-790.40	Dolerite (cataclastic) Breccia	Fill approximately 6-8mm thick Looks clastic with orangy rims	Poorly sorted Subangular to subrounded quartz	No fault evidence Weak clay alignment Minimal cataclasis Clast 'pushed' against dike wall Phyllosilicate rims around quartz grains Clay matrix Sharp, planar contacts Unknown direction	Oriented F#: 2309
821.12-821.17	Dolerite clast conglomerate and quartzose sandstone	Clastic? 2-4mm complex <i>en echelon</i> vein pattern within and along margins	Abundant clay matrix	Clastic injections Parallel veins Wide range of grain size. Angular grains Cataclastic zone Late calcite <i>en echelon</i> veins (tensile?) Upward injection	Will be oriented F#: 2443 Dip: 75°

The matrix inside the dikes has been completely replaced by calcite in one section and by pyrite in the other. Within one dike, there is well developed clay alignment parallel to the dike walls, but only localized and patchy orientation in the other. The dikes are discrete, planar zones, with sharp contacts, but they bulge around clasts where clasts had 'pushed' against the dike margins, probably due to later compaction. This is more conspicuous in one of the thin sections, where the host rock lithology is finer-grained.

Injection direction from these samples can be deduced by the tapering upward 'apophysis' in one of the thin sections (Figure 11). The injection direction is inconclusive in the other thin section, but a thinning upward branch also suggests a possible upward direction. Even though the discrete and sharp planar boundaries of the dikes may suggest the sediment was cohesive at the time of emplacement, there must have been some degree of pore fluid in the sediment in order for the liquified dike material to be injected.

There is no fracturing, grain size reduction or fabrics in the host rock along the margins of the dikes that would suggest a pre-existing fault fabric. This suggests these are sedimentary injections along opening-mode fractures.

Clastic dikes in dolerite breccia

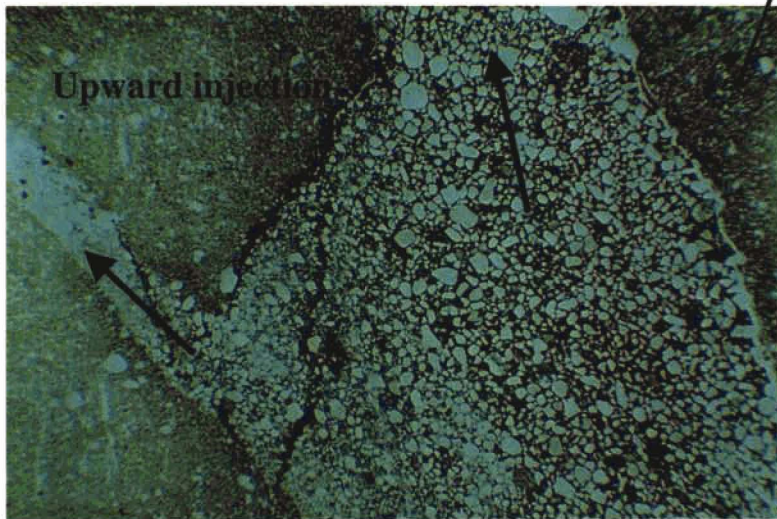
These thin sections 790.37-790.40, and 821.12-821.17 are clastic dikes injected in dolerite boulders within dolerite breccia, within a possible shear zone (Table B).

One of the clastic dikes exhibits sharp, planar contacts, and is filled with sandstone grains, which are poorly sorted, subangular to subrounded in a clay matrix. Clay alignment parallel to the clastic dike walls is weakly developed.

The second thin section is more complex because this is not a planar band, but rather a multiple branching injection with abundant clay matrix, poorly sorted, subangular to subrounded quartz grains, all within an altered dolerite clast. Multiple thin veins with a fibrous calcite fill arranged in *en echelon* patterns frame both the dike and the dolerite clasts (Figure 12).



'Unrolled' Whole Core Scan



Photomicrographs. Plane light

Figure 11. Upward injections of dike material at 194.50 mbsf.

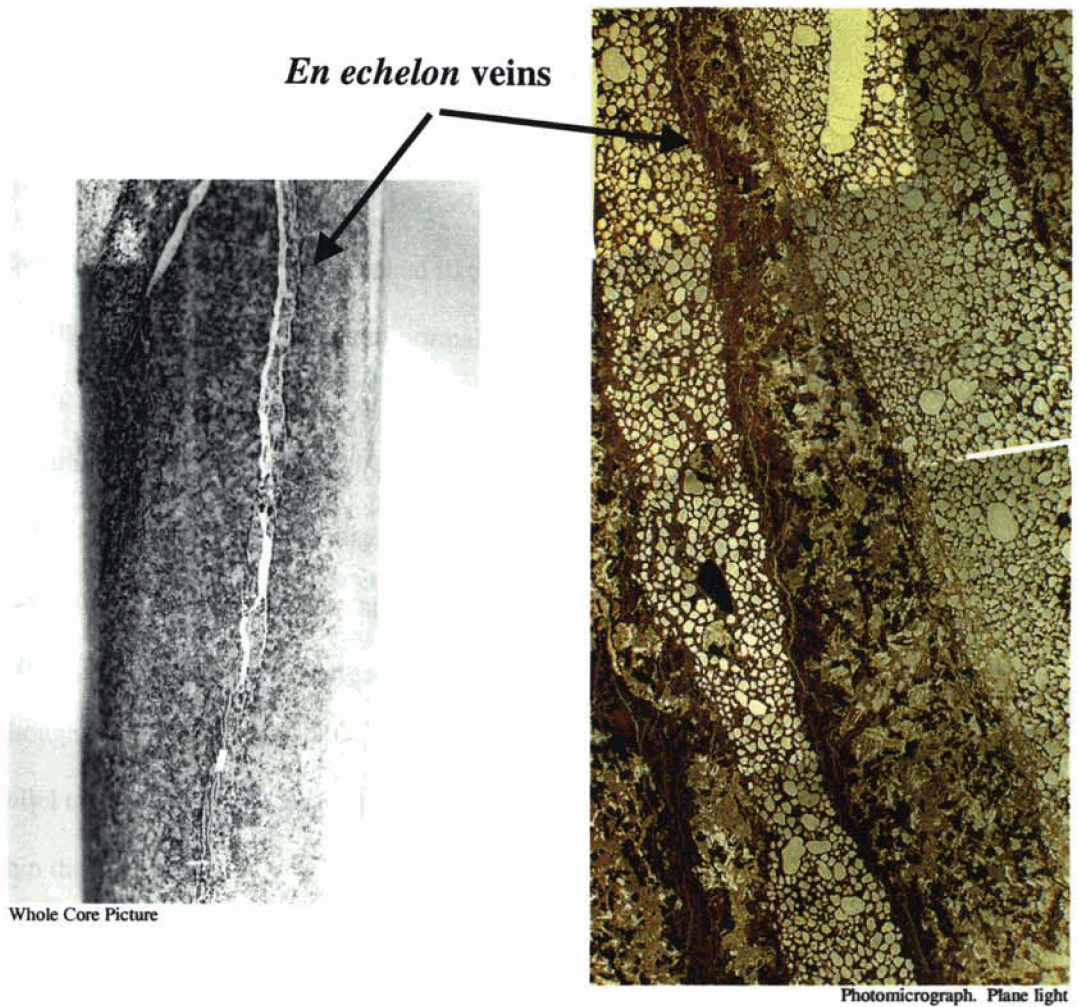


Figure 12. Multiple, branching clastic dike. Note alteration of dolerite to brown clay material, abundant clay matrix in dike on left and clasts of dolerite within dike. Later, *en echelon* calcite veins have formed along with dike margins indicating later shear. Depth 821 mbsf.

These veins suggest minor shearing along the dike margins may have taken place at a later stage. Those dikes found to crosscut hard rock—dolerite clasts—have no evidence of fracturing and/or faulting and must, therefore, be opening-mode fractures (Figure 13).

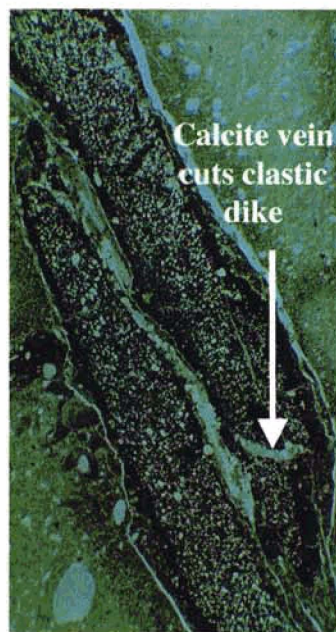
Veins

Veins with fault dips and veins with en echelon geometry

These three thin sections 97.95-97.99, 143.87-143.91, and 194.15-194.19 (Table C) are grouped together because they looked like calcite veins at the macroscopic level. In addition, their dip angles, similar to those of normal faults, suggest these features may have followed pre-existing fault planes at the time of formation.

Rather than being simple calcite veins as the macroscopic logging inferred, three of these are sharp, planar bands of clastic material. They are filled with grains that are moderately to poorly sorted, coarser than those of the host rock, subrounded to subangular, and with minimal or no fractures or intragranular deformation within them, and therefore must be injected clastic dikes. Although some injections exhibit weak or localized alignment of clays and/or quartz grains parallel to the injection margins, most of them have abundant, strongly oriented clay fabrics within them. Branches and apophyses in two of the sections taper upwards and can be used to infer upward injection direction.

The host rocks in this group are varied in their textures, fabrics, and lithologies. A fabric is very weakly defined in one of the samples by alignment of grain long axes parallel and adjacent to the dike margins. Two have local or discontinuous rims of material that is finer-grained than the host rock. The fabric and change in grain size could be the result of faulting prior to clastic injection. Some of the dikes exhibit truncation and normal offset of bedding across them, and in one case, one of the dikes clearly crosscuts and offsets another with normal sense. Other samples



Photomicrograph. Plane light



Half-Slab Core Scan

Figure 13. Pyritized clastic dike with calcite veins along margins and cutting dike. Overlapping dike tips are typical of opening-mode tensile fractures. This dike has similar strike and dip as normal faults in the core. Possibly the dike opened a pre-existing fault plane.
Depth 143.87 mbsf.

Table C

VEINS						
SECTION ID DEPTH	HOST ROCK LITHOLOGY	MACRO- STRUCTURES	VEIN FILL	TEXTURES	CONCLUSIONS FROM TEXTURES	ATTITUDE
97.95-97.99	Clast-poor sandy diamictite	3-4mm vein (calcite and pyrite)	Sand-filled sedimentary dike Coarser grained than host rock Subrounded to subangular grains Sharp planar margins No fabric evident Abundant dolerite and granitoid clasts Normal sense offsets bedding	Weak clay alignment in dike edges on host rock Sharp planar edges Dolerite lonestones pushed against dike walls due to composition Weak grain alignments No pyrite or calcite Upward injection Partially lithified sediment and later compaction	Clastic dike following pre- existing fault plane	Will be oriented F#: 319 Dip: 77°
143.87-143.91	Sandy mudstone with disperse clasts	Pyrite filled calcite veins fracture <0.5mm wide Clastic intrusion: opening made faults? <i>En echelon</i>	Wavy, overlapping tips Pyrite replacing matrix Subangular, well sorted sandstone	Host rock clay strongly oriented parallel to dike margins Possible normal shear sense? No clear bedding Branches Upward injection	Opening-mode fracture followed by clastic dike Possible followed pre-existing fault plane?	Will be oriented F#: 818 Dip: 60°
194.15-194.19	Muddy fine- grained sandstone Vein-fault?	Calcite and pyrite Patchy and wavy	Thin horizontal calcite vein replacing previously offset bed Two clastic dikes Sandstone coarser than host rock Minor calcite replacement Minor clay orientation within dike	No fabric within host rock One clastic dike follows fault plane and offsets other dike Wavy irregular edges Normal sense Unknown injection direction	Clastic dike emplacement followed by faulting Another dike following pre- existing fault plane Late calcite replacement of bed matrix	Will be oriented F#: 581 Dip: 79°

Table C

VEINS						
SECTION ID DEPTH	HOST ROCK LITHOLOGY	MACRO- STRUCTURES	VEIN FILL	TEXTURES	CONCLUSIONS FROM TEXTURES	ATTITUDE
267.34-267.38	Sandy mudstone	<i>En echelon</i> segments Vein-fault?	Clean fibrous calcite perpendicular to walls	Tapering tips Opening mode No fault evidence No fabric-bedding in host rock	Opening mode fracture and vein precipitation	Not oriented F#: 181 Dip: 60°
104.01-104.05	Clast-poor sandy diamictite	Patchy light-gray vein Appears conjugate	Finer-grained than host rock More uniform Contains dolerite clasts	Irregular shape Possible tapering 'branch' Discontinuous bedding; cannot tell if truncates Clay rich band oblique to vein walls Probably related to injection Upward injection?	Clastic injection No faulting evidence	Will be oriented F#: 334 Dip: 30° F#: 335 Dip: 28°
112.37-112.41	Clast-poor sandy diamictite Muddy fine- grained sandstone with dispersed clasts	Grey patches 4mm wide dikes Stands up in relief 2mm	Fine-grained sandstone Upward grain size/composition change. Subangular to angular grains	Mineralized fill in dikes No apparent bedding Clay parallel to wall within upper dike Meet at intersection but not seen in thin section Relief due to low clay content Thinner tapered upward Upward injection	Two clastic dikes No faulting evidence Tapered upward may indicate upward injection	Will be oriented F#: 388 Dip: 55° F#: 389 Dip: 53°
263.96-264.00	Medium to coarse grained sandstone with abundant pebble sized clasts Poorly sorted Subrounded to subangular	White calcite Grey bands/faults?	Similar grain size to host rock Subrounded to subangular Abundant clay all replaced by calcite	Not very planar dikes defined by calcite and local pyrite replacement Clastic dike indicated by margins of the dike wrapping around clasts no truncated them	Clastic dike No faulting evidence	Not oriented F#: 794 Dip: 63° F#: 795 Dip: 80°
166.65-166.69	Sandy mudstone with dispersed clasts	Grey band Normal sense fault?	Foliated clay parallel to walls No fabric within rhomb	Rhomb filled by clay that grew during shear Normal bedding offset No fabric in host rock No cataclasis evidence	Normal fault	Will be oriented F#: 518 Dip: 65°

Table C

VEINS						
SECTION ID DEPTH	HOST ROCK LITHOLOGY	MACRO- STRUCTURES	VEIN FILL	TEXTURES	CONCLUSIONS FROM TEXTURES	ATTITUDE
191.85-191.89	Muddy sandstone with disperse clasts	Grey patches No fizz Vein? Fault?	Finer grained than host rock Weak clay alignment parallel to walls Scattered xenoliths similar to host rock?	Sharp, planar contacts No clay alignment or bedding in host rock Unknown injection direction	Clastic dike possibly follows fault	Will be oriented F#: 576 Dip: 50°
281.63-281.67	Well stratified medium grained sandstone with dispersed clasts	Grey band Truncates laminae Fault?	Grain size similar to host rock Little clay	Disturbed bedding in both sides of dike and offset not clear Cohesive enough to fracture (no muddy rock) but still unlithified enough to allow dike to pass	Clastic dike possibly follows fault plane opened space	Will be oriented F#: 885 Dip: 65°
345.11-345.15	Well-stratified sandstone Sandy mudstone and muddy sandstone with dispersed clasts and minor conglomerates	Cemented band with conjugate geometry Vein? Fault?	Similar to host rock but coarser in localized patches Calcite cemented	Conjugate geometry but no bedding or cataclastic evidence Cross-cutting not clearly established	Clastic Dike Ambiguous fault evidence	Will not be oriented F#: 1022 Dip: 65° F#: 1027 Dip: 66°

either lack bedding or, if present, it is discontinuous and therefore not indicative of possible offset.

Some level of cohesiveness was necessary in order for the dikes to have straight, planar margins as well as for the truncation of bedding to occur. However, the emplacement of sediment injections and the presence of clasts pushing against the dike margins—observed in two of the dikes and possibly the result of later compaction of the rock—indicates that the sediment must have been only partially lithified and later compacted.

The structural macroscopical characteristics assigned to this group can now be revised and corrected. At least two of the injections exhibit normal shear sense offsets. Together with the fact that their dip angles are consistent with those of normal faults, this suggests these clastic injections used weakened, pre-existing fault planes as dewatering channels.

One sample, 267.34-267.38 (Table C), also exhibits a dip angle like that of a fault, however the nature of the vein makes it somewhat different than the others in this group. Macroscopic observation revealed this vein has an *en echelon* geometric pattern. Fibrous calcite crystals grow almost perpendicular to the dike walls and a 'median line' is clearly seen. The host rock contains abundant quartz that becomes finer-grained in patches along the vein margins. Its overlapping, tapering tips and *en echelon* geometry indicates this is an opening-mode fracture rather than a clastic injection.

Calcite veins with conjugate geometry

The three thin sections in this group 104.01-104.05, 112.37-112.41, and 263.96-264.00 (Table C), have the macroscopic appearance of calcite veins, and their conjugate geometry suggests they may have precipitated into pre-existing, normal fault planes.

The 'veins' were found to be filled with fine-grained sandstone that is similar or slightly finer than the host rock and with more uniform grain size, but with a wider range of grain shape and therefore are clastic dikes. The dikes are somewhat irregular, with wavy walls, apophyses, and a

change of character both across and along the injection—grains becoming finer or coarser, and clay content increasing or becoming patchy. Clay content varies from sample to sample, but in general these are clay-poor injections where calcite—and pyrite in cases—has filled the pore spaces. Pyrite is relatively abundant and is often accompanied by flaky, high birefringence grains that have a random orientation.

The lack of fabric in the host rock as well as the discontinuous bedding and/or poorly developed bedding prevents detection of any fault offset. Microscopic observation of the samples reveal these are likely to be clastic injections, however, no faulting evidence has been found that can explain the conjugate geometry.

Cemented bands

This group of four thin sections 166.65-166.69, 191.85-191.89, 281.63-281.68, and 345.11-345.15 (Table C), comprised macroscopic core fractures that looked like discrete bands cemented by calcite. Most exhibit fault characteristics such as bedding offset, conjugate geometry, and sharp, planar boundaries.

Microscopically, these samples have a wide range of characteristics. Three of four have clastic fill material of similar composition to that of the host rock, moderately sorted, finer-grained than the host rock and with localized patches of coarser grains. One dike exhibits strong clay alignment parallel to the margins, whereas the others only have weak alignment or very little clay without orientation. Calcite replacing clay matrix within the dike is sparse and localized, except in one injection where it defines the boundaries.

Fabrics in the host rock are not well defined since there is little or no clay in the sandstone and sandy mudstone lithologies. Only one of the injections clearly truncates laminae, but disturbed and discontinuous bedding on both sides of the dike prevents detection of any displacement. One of the samples is a definite fault. The macroscopic band consists of anastomosing surfaces lined by patches of well-oriented clay. Along the main surface there is a

rhomb containing randomly oriented clay that grew in open space (Figure 14). The rhomb geometry, as well as bedding offset, is indicative of a normal sense of shear. The other two sections do not exhibit clear textural evidence of faulting, however, one of them has a boundary across part of the host rock that matches the dike margins right above and below it and where clay alignment seems to be relatively stronger. This may possibly be the remnant of an old fault plane.

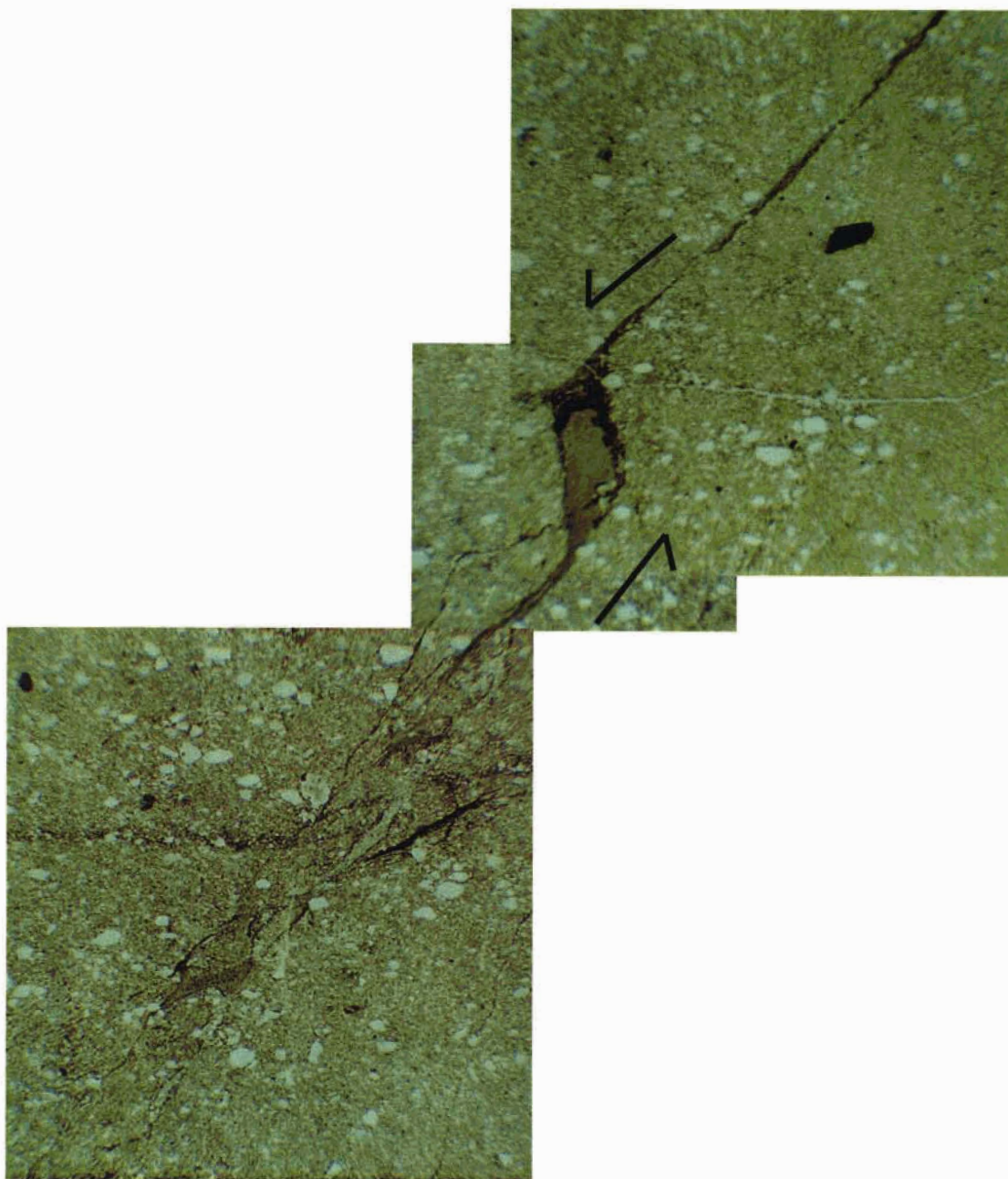
Three of these samples represent clastic dikes that followed pre-existing fault planes as suggested by the clay orientation, geometry and vague bedding offset. The sharp and planar boundaries of the dikes suggest the sediment must have been cohesive at the time of emplacement, however, at least partially lithified sediment was needed for the liquefied dike material to be injected.

The clay-filled, open-rhomb geometry of the other band and the abundant clay lining the fault surface, together with the shear sense defined by the rhomb geometry and offset bedding indicates this is a normal fault. These textures are commonly associated with cataclastic faults in cohesive sediments, however they are also known to occur in partially lithified sediment at shallow depths.

Microfaults

Shear zones in partially lithified to unlithified sediment

The thin sections in this group are 161.01-161.05, 290.29-290.33, 316.11-316.16, and 465.15-465.19 (Table D). They are all characterized by macroscopic observations of bedding offset—both reverse and normal sense—across discrete, planar zones and smearing and/or dragging of sediment along the zones. These features are suggestive of soft-sediment shear zones, where the sediment was only partially lithified to unlithified at the time of deformation (Figure 15).



Photomicrograph. Plane light.

Figure 14. Normal offset of bedding. Clay lining fault surface has strong preferred orientation parallel to walls and fills rhomb that opened during shear.
Depth 166.65 mbsf.

Table D

FAULTS					
SECTION ID DEPTH	HOST ROCK LITHOLOGY	MACRO- STRUCTURES	TEXTURES/ FABRICS	INTERPRETTED FAULT MODE KINEMATICS	ATTITUDE
161.01-161.05	Sandy mudstone with dispersed clasts	Cuts soft-sediment shear zone Normal fault Calcite vein	Nearly planar fracture fill with calcite and clay. Calcite fill grew perpendicular to walls in open space of major fracture which suggests opening-mode Strongly oriented clay parallel to fracture walls Cuts soft-sediment Clay orientation defines soft-sediment shear zone Where is clay coming from?	Soft-sediment shear zone Normal sense	Will be oriented F#: 502 Dip: 45°
290.29-290.33	Well stratified medium-grained sandstone with dispersed clasts	Offset bedding	Reverse fault Pachy calcite cement Alignment of grains parallel to fault planes Small drag of sediment into fault but some discrete planes Normal fault Thinner zone with more discrete plane probably material is more cohesive (so younger) Faults stop abruptly into more porous coarser-grained sediment above	Cataclastic fault Two reverse sense One normal sense	Will be oriented F#: 909 Dip: 50° F#: 910 Dip: 51°
316.11-316.16	Interbedded muddy fine- grained sandstone with sandy mudstone	Offset bedding Soft-sediment?	Some alignment of grains Drag and smearing of bedding across fault zone Seems more diffuse when entering coarser grain zone above loses discreteness and 'fans' out	Shear zone Soft-sediment deformation Reverse sense	Will be oriented F#: 970 Dip: 70° to 80°
465.15-465.19	Clean, well- sorted, light colored quartzose sandstone Fine-grained	Cement band Conjugate normal fault Vein	More matrix in fault zone and replaced by calcite No grain size and shape change with respect to host rock No clear fabric features Localized minor clay alignment parallel to shear zone No cataclastic features Where is clay coming from?	Probable soft- sediment shear zone (based on macroscopic observations) Normal offset (based on macroscopic observations)	Not oriented F#: 1413 Dip: 80°

Table D

FAULTS					
SECTION ID DEPTH	HOST ROCK LITHOLOGY	MACRO- STRUCTURES	TEXTURES/ FABRICS	INTERPRETTED FAULT MODE KINEMATICS	ATTITUDE
52.65-52.69	Sandy mudstone with dispersed dolerite clasts	Possible 'crack- seal' morphology Definite dip-slip striae	Calcite crystals growing into rhombic shape voids Foliation defined by strong clay orientation Compound (parallel) veins indicate opening-mode Minor calcite twinning Vein precipitation and faulting are synchronous	Definite cataclastic injection 'Stair step' indicates reverse sense, but calcite rim on clast suggests normal sense	Not oriented F#: 150 Dip: 76°
135.27-135.31	Sandy mudstone with dispersed clasts	Calcite crystals perpendicular to vein walls Striae Open 'geodes' along vein Fault surface Calcite vein	Calcite crystals grow into open voids Stockwork veining Vein material fills breccia Minor calcite twinning Brecciated host rock suggests cohesive state sediment	Conjugate fault Fault breccia? Inconclusive	Will be oriented F#: 419 Dip: 70° Strike: 90° down-dip
148.33-148.38	Poorly sorted medium-grained sandstone with interbedded clasts	Brecciated host rock floating in calcite matrix Calcite cemented breccia	Calcite vein with crystals parallel to vein margin Brecciated host rock with calcite filling open spaces Minor clay-filled vein Fault like dip Cohesive state of sediment	Shear zone Fault breccia?	Not oriented F#: 454 Dip: 65° F#: 455 Dip: 73°
159.93-159.97	Sandy mudstone with dispersed clasts	Slickensides Calcite cemented fault	Well developed clay alignment Localized alignment of quartz grains Pressure shadows on clast Bedding offset	Cataclastic fault Normal sense	Will be oriented F#: 497 Dip: 51°
407.76-407.80	Mudstone with interbedded sandstone	Calcite slicken- fiber steps Conjugate array	Diffuse boundaries defined by calcite cement Minimal grain and clay alignment Fracture shows finer and angular grains and more clay Minor sparry calcite No bedding	Cataclastic fault F# 1238 Normal sense F# 1236 and 1237 Inconclusive	F#: 1236 050, 68NW F#: 1237 280, 75SW F#: 1238 015, 64W

Table D

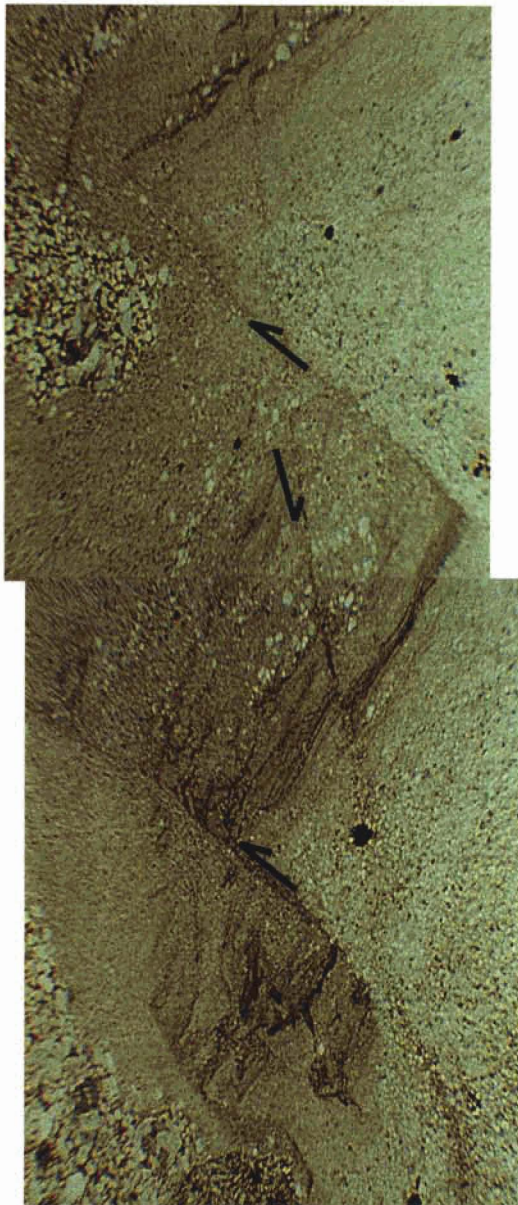
FAULTS					
SECTION ID DEPTH	HOST ROCK LITHOLOGY	MACRO- STRUCTURES	TEXTURES/ FABRICS	INTERPRETTED FAULT MODE KINEMATICS	ATTITUDE
461.72-461.77	Sandstone and mudstone Fine-grained sandstone Sandy siltstone Silty claystone	Conjugate Offset bedding Black bands drag bedding Normal faults	Minor grain alignment parallel to fault boundary Carbonate and pyrite mineralization on fault plane Clay is more abundant in fault zone Sharp truncation of bedding by fault Grain size and shape in fault zone similar to host rock Silty deformed bed Minor drag of bedding	Cataclastic fault Normal sense 1395 offset by 1394	F#: 1394 000, 73W F#: 1395 338, 70NE
538.86-538.90	Quartzose sandstone Thin section: dolerite boulder	Thick zone calcite cement Sediment constrained by fragments in calcite fault zone Vein-normal fault	No preserved fabric Sharp planar dolerite/sandstone contact preserved in breccia fragment No strike <i>In situ</i> jigsaw-puzzle fracture grains Styolitic 'teeth' cuts calcite vein suggests local pressure solution Brecciated host rock implies cohesive sediment	Cataclastic fault Normal sense 6 cm normal displacement minimum	Not oriented F#: 1642
818.26-818.30	Quartzose sandstone with pebbles, cobbles and boulders Well sorted, stratified sandstone	1-4mm elastic fill Offsets bedding and injects up into base of clast Normal fault	Fabric parallel to dike margins Grains near margin are more broken down Thin vein cuts sandstone and dike Angular grains in fault zone	Cataclastic fault? Normal fault	Not oriented F#: 2427
823.29-823.33	Light red-brown quartz sandstone Medium-grained	Offset	Finer grain than host rock Angular grains within zone (small) from host rock Randomly oriented upward birefringence clay Truncates bedding Clay not likely from host rock Irregular interior walls of zone due to 'plucked' out grains	Cataclastic fault?	Oriented F#: 2451 067, 78NW F#: 2452 067, 72NW
845.37-845.41	Light red/brown quartz sandstone	Calcite cemented Offsets bedding	Finer grained than host rock but same composition Some <i>in situ</i> fractured grains Intragranular fractures Grain alignment parallel to fault margin Clay matrix (abundant) not likely from host rock	Cataclastic fault?	Oriented Dip: 57°

Fabrics defined by clay alignment are common in these fault zones. The clay fabrics are similar to fault zones interpreted to have formed in cohesive to lithified material. No intragranular deformation, fractured grains, or brecciation of the host rock and/or shear zone material are observed in these faults. Localized alignment of grain long axes parallel to the zone boundaries is typical. The shape and size of grains within zones is often similar to those of the host rock, however, some of the shear zones have abundant clay matrix in much greater proportion than in the host rock. The clay material may have been transported into the zone by fluids, or may represent alteration or recrystallization of pre-existing matrix. A more detailed study of these thin sections will be necessary to resolve this matter.

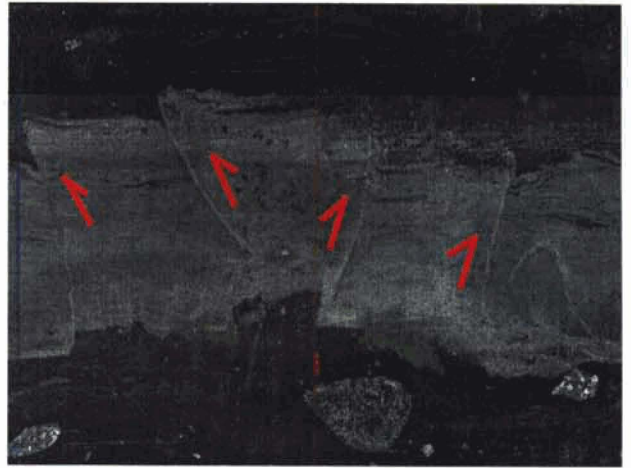
Most of the calcite seen in this group is a replacement of clay matrix in the fault zones. Veins are rare and those observed are only thin fractures with a few, small calcite crystals. In only one thin section, a vein with larger crystals perpendicular to the vein margins indicates an opening-mode vein in more cohesive sediment.

In two of the thin sections faults stop at lithologic boundaries, either bedding planes or other fault zones. The faults are well defined in finer grained host rock but die out into less dense, more porous, coarser-grained material. In one case, the discrete fault zone terminates abruptly at the contact, whereas in the other, the zone seems to 'fan' out, and die. The ability of the grains to slide past each other and rotate in lithologies with more open space, may have accommodated the shear beyond the tips of the more discrete, contained shear zones.

Other typical characteristics of this group of faults is bedding drag and/or smearing of sediment along the fault zone (Figure 16). Drag is ductile behavior, and the flow of sediment along fault planes implies the sediment at the time of faulting must have been unlithified or only partially lithified. These faults are interpreted to be 'shear zones' in the sense of Maltman (1994), developed before complete lithification. Calcite replacement of the matrix, hairline fractures filled with calcite crystals and, in one case, a discrete, narrow fault plane lacking sediment drag, are all later deformation processes, formed when the sediment was more cohesive.



Photomicrograph. Plane light



'Unrolled' Whole Core Scan

Figure 15. Soft-sediment shear zones with reverse displacement interpreted to indicate pre-lithification faulting. Depth 290.29 mbsf.

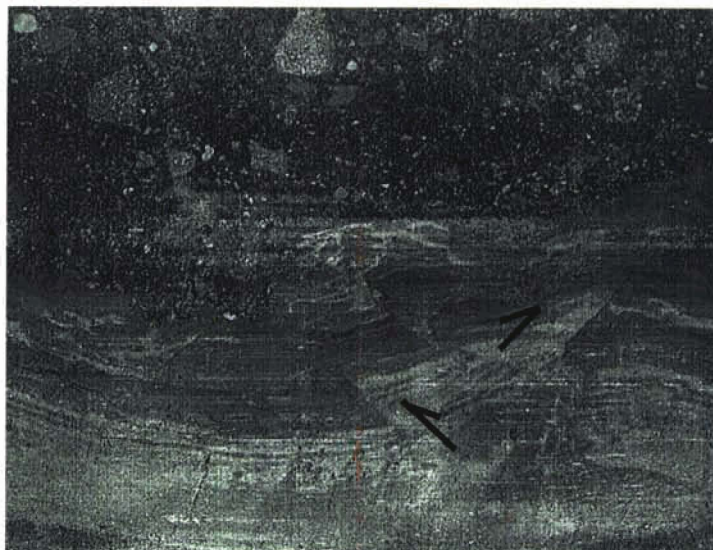
Faults in cohesive to lithified sediment

This group of seven thin sections (52.65-52.69, 135.27-135.31, 148.33-148.38, 159.93-159.97, 407.76-407.80, 461.72-461.77, and 538.86-538.90) (Table D), are all of dip-slip, discrete faults of known or probable normal shear sense motion and, in most cases, with well developed slickensided surfaces.

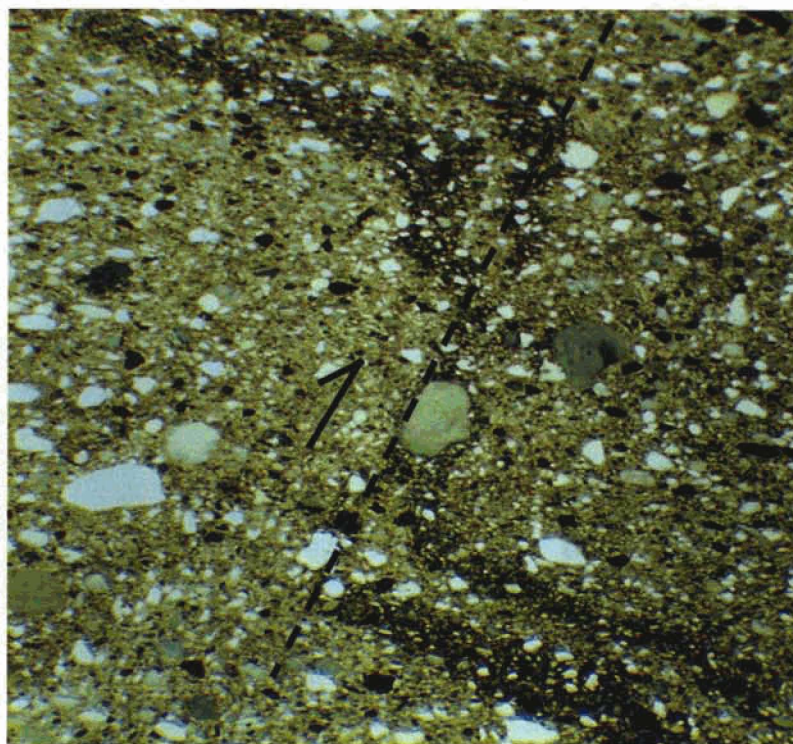
The fault zones vary in scale from just 0.2 mm discrete bands to zones up to 2 cm wide or even greater, which cannot, therefore, be preserved in thin section. Several of the fault zones exhibit fabric defined by clay orientation and alignment of grain long axes. Less commonly, fabric is defined by wrapping of clays around clasts, stylolites (Figure 17), pressure shadows around clasts and, in one case, an asymmetric tail around a clast (Figure 18). These last two textures have also been used as kinematic indicators, either on their own or in combination with bedding offset and void geometry to confirm the sense of shear motion. Brecciation of the host rock with calcite precipitated in open spaces is the dominant texture in three of the sections. Together with some *in situ* fractured grains, this indicates cataclasis of cohesive material during faulting.

All of these faults except one have parallel veins of clean, sparry calcite as the most common fill. Only a few small, opening-mode veins have fibrous calcite. Some calcite grows from clast margins, but it typically grows into open voids, fills spaces in the brecciated host rock or replaces clay as cement. In two of the thin sections, sparry calcite grew into open voids with a vaguely rhombic geometry (Figure 18).

Other common characteristics of this group of faults is the cohesive state of the sediment as evidenced by the angular breccia clasts, the generally clean, equant crystal geometry filling open voids, quartz grains displaying 'jigsaw puzzle' fracturing and, in one section, the preserved planar contact between dolerite and sandstone in fragments within the fault zone (Figure 18).



'Unrolled' Whole Core Scan



Photomicrograph. Polarized light

Figure 16. Shear zones with reverse displacement. Note flexure of bedding interpreted to indicate pre-lithification faulting.
Depth 316.11 mbsf.

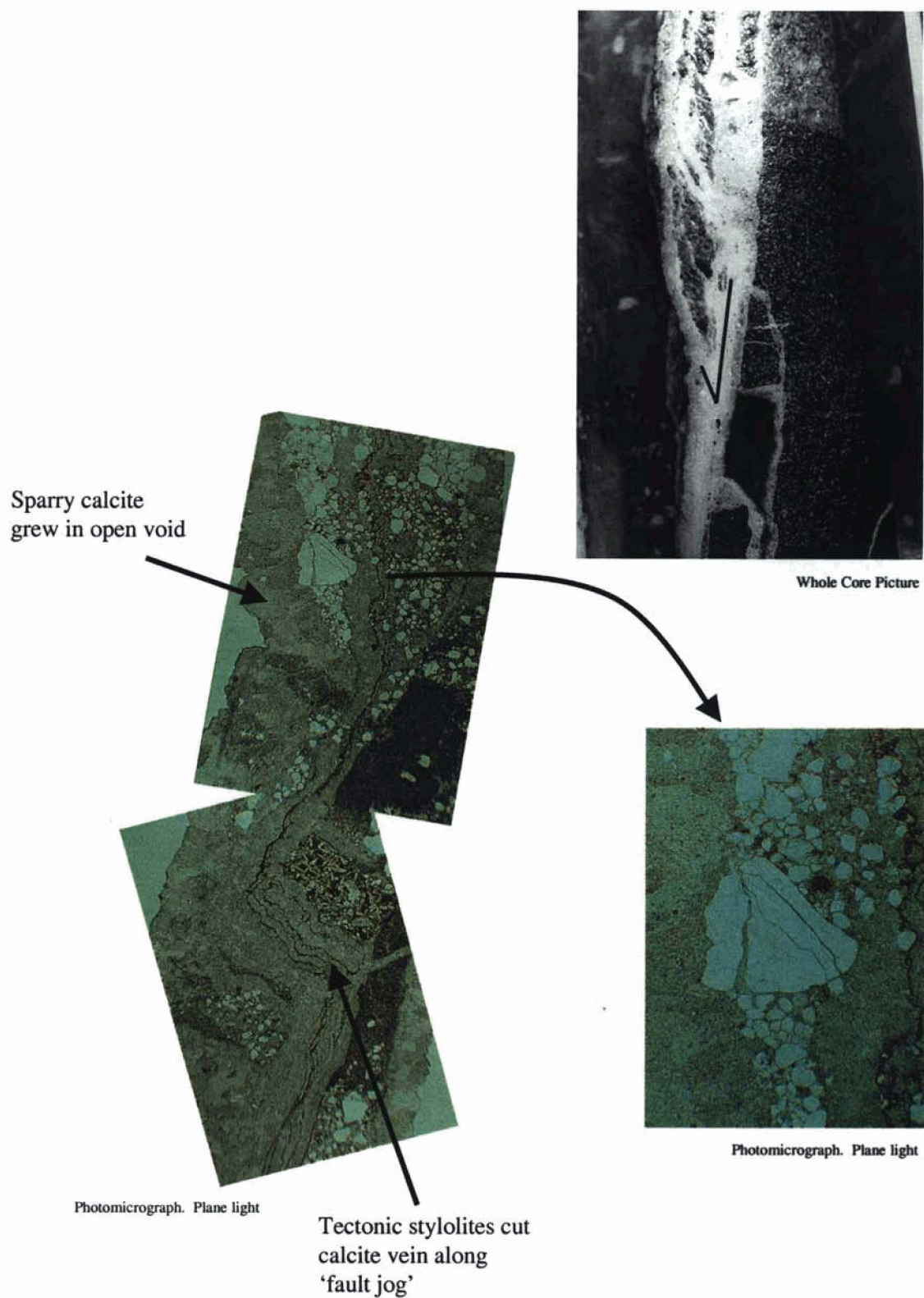


Figure 17. Lowermost surface of inferred larger fault zone at c. 539 mbsf. Note normal sense offset of pale sandstone above dolerite boulder and thick calcite vein following fault. Thin sections show grain breakage along fault zone overgrown by calcite.

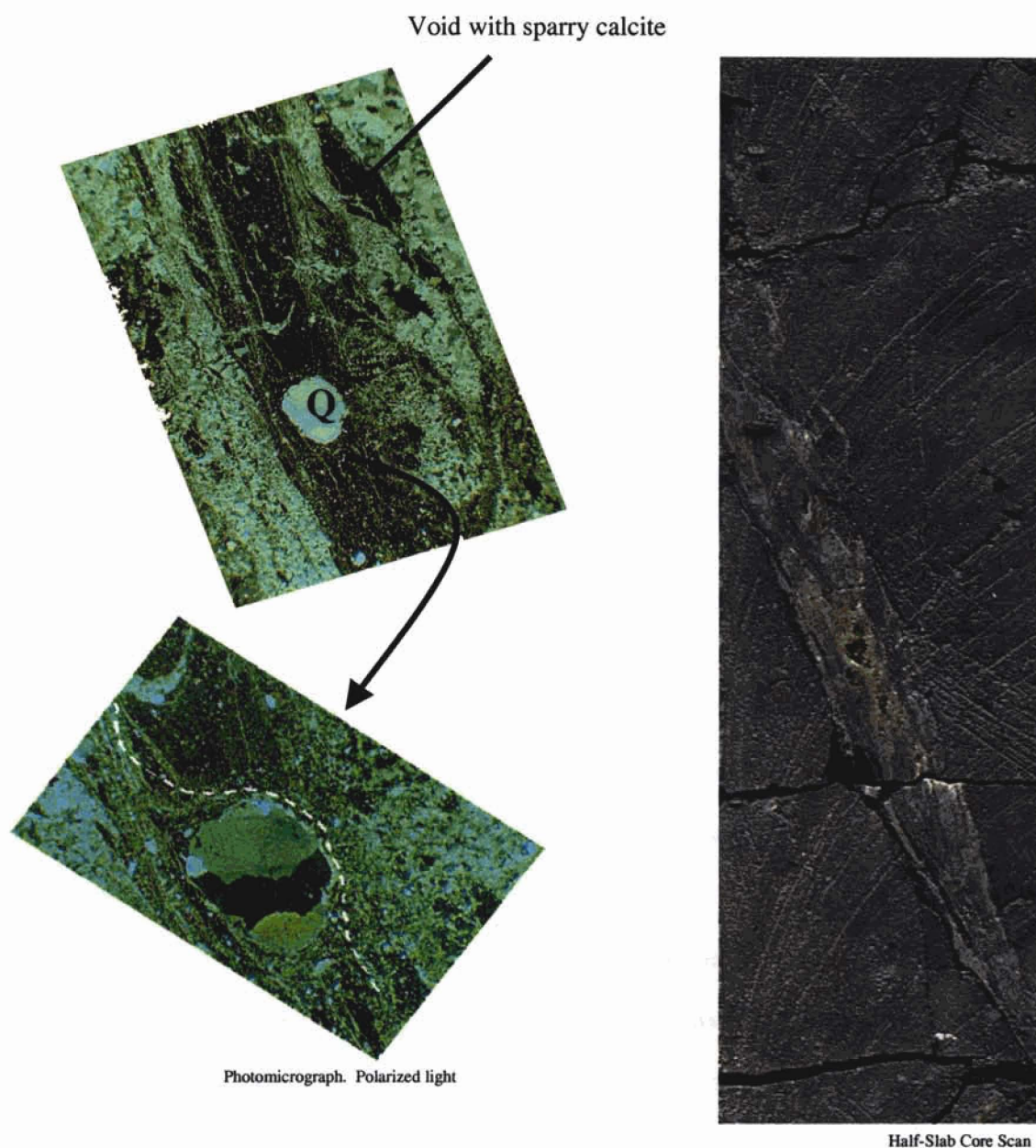


Figure 18. Fault zone overgrown by calcite veins. Large quartz clast shows asymmetric 'tails' indicating normal-sense shear. Sparry calcite has grown into open void. Depth 52.65 mbsf.

Most commonly the relative timing of events suggests that calcite precipitated within the fault zones at the same time as shearing was taking place. Indicators in support of synchronous faulting and calcite growth are crosscutting structures, veins filling open spaces in the brecciated host rock, and the rhombic geometry observed in calcite-filled voids. Minor calcite twinning in some thin sections implies that at least some shearing must have occurred after calcite filling.

The characteristics observed in this group of faults are consistent with brittle cataclasis of cohesive, partially lithified to lithified material in the presence of abundant fluids.

Faults in the Beacon Sandstone

Three samples are of faults within the Beacon Supergroup of Devonian age 818.26-818.30, 823.29-823.33, and 845.37-845.41 (Table D). The Beacon is characterized by medium-grained, clean, well sorted, quartzose sandstone of a light red-brown color. This sandstone must have been lithified when faulting occurred in the Oligocene. All three faults exhibit macroscopically observable discrete, planar zones, and sharp truncation and offset of bedding. Normal offset of bedding observed in these sections range from c. 2 mm to 7 mm, and is easily observed because the Beacon is generally well stratified.

The fault zones are characterized by abundant very fine-grained quartz aggregates (=gouge?), or by angular quartz fragments dispersed with a brown clay matrix or a matrix of high-birefringence mica. In one of the samples, the very fine-grained 'clay' is intermixed with patches of yellow-orangish high birefringence mica, possibly an alteration product. Within this matrix there are quartz grains of the same size and composition as those of the host rock, likely to have been 'plucked' out from the walls of the fault, however, abundant smaller, angular fragments, also derived from the host rock, are present. The host rock grains commonly exhibit *in situ* and intragranular fractures, and grain size reduction near the fault margins. Calcite in these thin sections is rare and only observed in small, thin fractures where small, very clean sparry crystals grow into open spaces; calcite cement is almost non-existent.

The evidence of cataclasis of the quartz grains observed in these zones is interpreted as the result of brittle faulting of material that was fully lithified at the time of deformation.

DISCUSSION AND CONCLUSIONS

The identification and evaluation of microscopic characteristics such as grain-scale structures and textures, together with the known deformation conditions encountered at the CRP-3 site, can be used to interpret the deformation mechanisms that produced the structures, the state of the sediment at the time of deformation, and the relative timing of the deformation that took place.

Clastic dikes are more common than the previous macroscopic evaluation of the core had predicted. Thin section analysis showed that many structures logged as 'veins' are actually thin, fine-grained clastic injections. The clastic dikes are characterized by sharp, planar boundaries with a fill that is always different than, and typically coarser-grained than, the host rock. They also commonly change in character throughout their width and/or length, by changing grain size, abundance, and/or shape. Mineralization of matrix by calcite is often present either pervasively or just in localized patches. All of the dikes with clear indicators for emplacement direction showed upward injection.

The majority of the dikes truncate bedding and have dip angles between 50 and 70°, similar to those of normal faults. This suggests the dikes may have followed pre-existing fault planes. In many cases, this could be demonstrated by the presence of bedding offsets with normal sense displacement or where a dike cuts and offsets another dike. A variety of lithologies were encountered in the host rock, but most had a weakly developed fabric or no fabric at all. Rarely, the quartz grains within the host rock exhibited weak alignment of grain long axes parallel to the dike margins. Except in the dolerite breccia shear zone, almost none of the samples showed cataclastic structures within the host rock.

Because of the sharp and discrete nature of the boundaries in most dikes, it is likely the host sediment was cohesive at the time of dike emplacement. At the same time, source layers for the clastic material must have remained incompletely lithified. Also, some clasts in the host rock

were observed to indent into the dike margins, which is interpreted to be the result of sediment compaction post-dating dike emplacement.

The relationship between upward injection direction and normal bedding offset, together with the evidence for ongoing compaction processes, suggest that clastic dikes were most likely using 'young' pre-existing faults as dewatering channels during ongoing compaction and lithification of the Oligocene strata.

Veins, on the other hand, are not as common in these samples as macroscopical observations had predicted. Many pale, filled fractures were logged as either calcite veins or carbonate cement bands. Because most of these had either dips or conjugate geometries typical of normal faults, they were suspected to be mineralized faults. Most of the 'veins' and 'cement bands' were found to be clastic dikes that had been heavily mineralized.

Structures that proved to be mineralized veins were commonly associated with faults. These veins consist of relatively large, equant, clean, sparry calcite growing in open voids, filling open spaces in brecciated host rock and growing as rims around clasts. The rhombic geometry of the open voids and the dominant occurrence of calcite in brecciated host rocks, indicate shearing and vein precipitation were synchronous events. Some weakly twinned crystals suggest minor shearing must have taken place after crystallization. This type of vein clearly formed in sediment that was lithified.

Veins in which small, clean, fibrous crystals grow perpendicular to the vein walls are often small, hairline fractures and compound veins formed as opening-mode fractures. These commonly crosscut other structures and most likely post-dated compaction processes. Some exhibited *en echelon* geometry, with overlapping, tapering tips, typical of opening-mode veins. However, the most common occurrence of vein material throughout the core is in the form of calcite filling pore spaces within clastic dikes and faults, and replacing matrix in localized patches.

The microfaults were the most abundant structure in the core, and two types were found: shear zones in partially lithified to unlithified sediment, and faults in cohesive to lithified sediment. The shear zones are characterized by narrow, planar, zones where sediment drags and/or is smeared along the zone, grain deformation and grain breakage is minimal, and abundant clay and/or grains are oriented parallel to the zone margins. Also, the presence of clay in the shear zones is typically greater than in the host rock. The bedding offset observed in these samples reveals both normal and reverse sense motion. A few of these soft-sediment shear zones die out abruptly or splay before dying out where they enter a zone of coarser-grained, more porous material. This is likely due to grains accommodating shearing by moving and/or rotating in fluid-filled pore space. Minimal calcite replacement has been observed within the shear zones. The fabrics and textures in these samples suggest deformation took place in unlithified sediment by a ductile mechanism such as independent particulate flow, where grains slide past each other.

The fault zones are also planar zones of material finer-grained than the host rock defined by sharp, discrete boundaries. Most of the faults in which bedding offset was clear or other kinematic indicators were found, proved to be of normal sense. There was some grain scale evidence of cataclasis, such as *in situ* fractured grains. More commonly, however, the zones had more clay matrix than the adjacent host rock but lacked clear evidence of grain size reduction by fracturing. Alignment of clays and/or grains is common, as it is in the shear zones. Lithified sediment at the time of deformation results in brecciation of the host rock with associated calcite precipitation. These textures are consistent with cataclastic faulting mechanisms acting on partially lithified to lithified material.

The faults in the Beacon sandstone all are sharp, planar zones in which bedding truncation and offset are clear. Textures are dominated by intragranular fractures, increased angularity of grains and abundant fine-grained quartz that resembles gouge. The abundant fault zone matrix consists of brown clay and high birefringence flaky phyllosilicates that replace the gouge in patches. The evidence of cataclasis found in the faults cutting Beacon sandstone is consistent

with brittle shear of completely lithified sediment, as expected for Devonian rocks cut by Tertiary faults.

Clastic dikes, veins and faults are abundant throughout CRP-3 core and present at all depths and in a variety of lithologies. The microstructures and interpreted deformation mechanisms identified in this study indicate that clastic dikes and some veins followed pre-existing fault planes for emplacement and precipitation. Some of the faults are shear zones formed while the sediment was ductile and only partially lithified. Other faults showing brecciation and synchronous calcite precipitation in open space are the result of deformation in sediment that must have been lithified. This progression from pre-lithification faults to post-lithification faults indicates faulting along the Transantarctic Mountain Front must have been synchronous with the Victoria Land Basin rifting and deposition of the sedimentary fill of the rift basin.

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